PHENIX meeting, November 9, 2007

Exploring QCD at high energies and densities at RHIC: the next step

D. Kharzeev
BNL

BROOKHAVEN
NATIONAL LABORATORY

Outline

- What physics questions are we trying to answer?
- What have we learned from RHIC in the first five years?
- Why does it matter?
- What do we still want to know?

Four questions which drive the RHIC program

1. What are the phases of QCD matter?

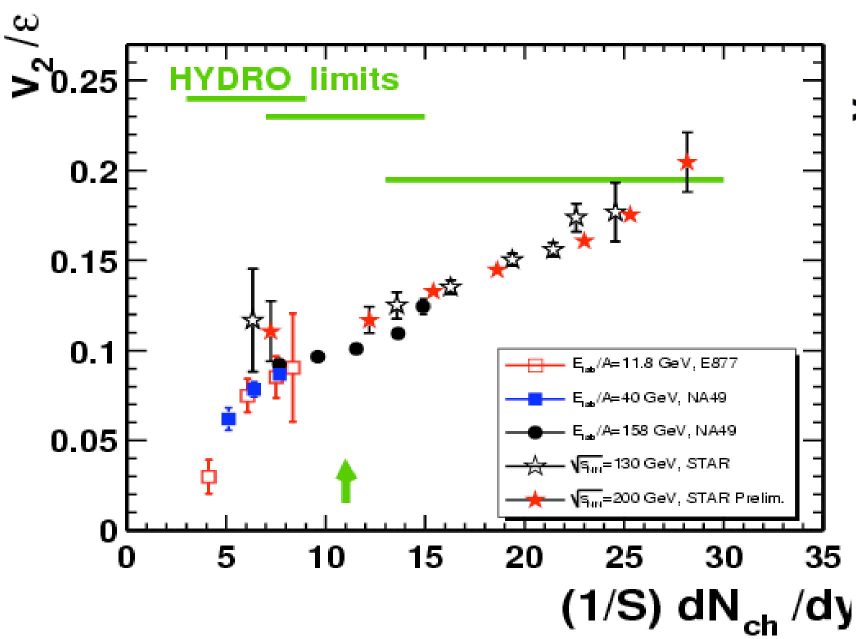
2. What is the wave function of the proton?

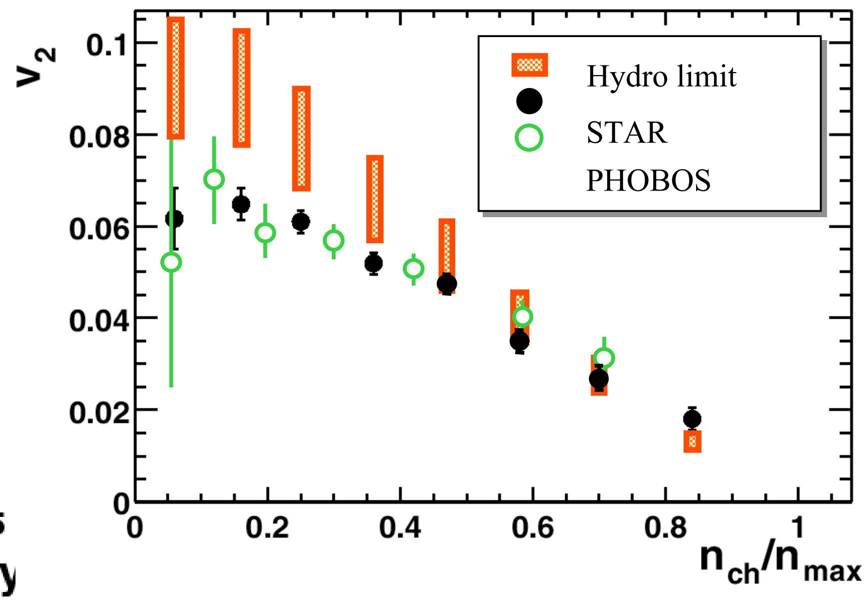
3. What is the wave function of a heavy nucleus?

4. What is the nature of non-equilibrium processes in a fundamental theory?

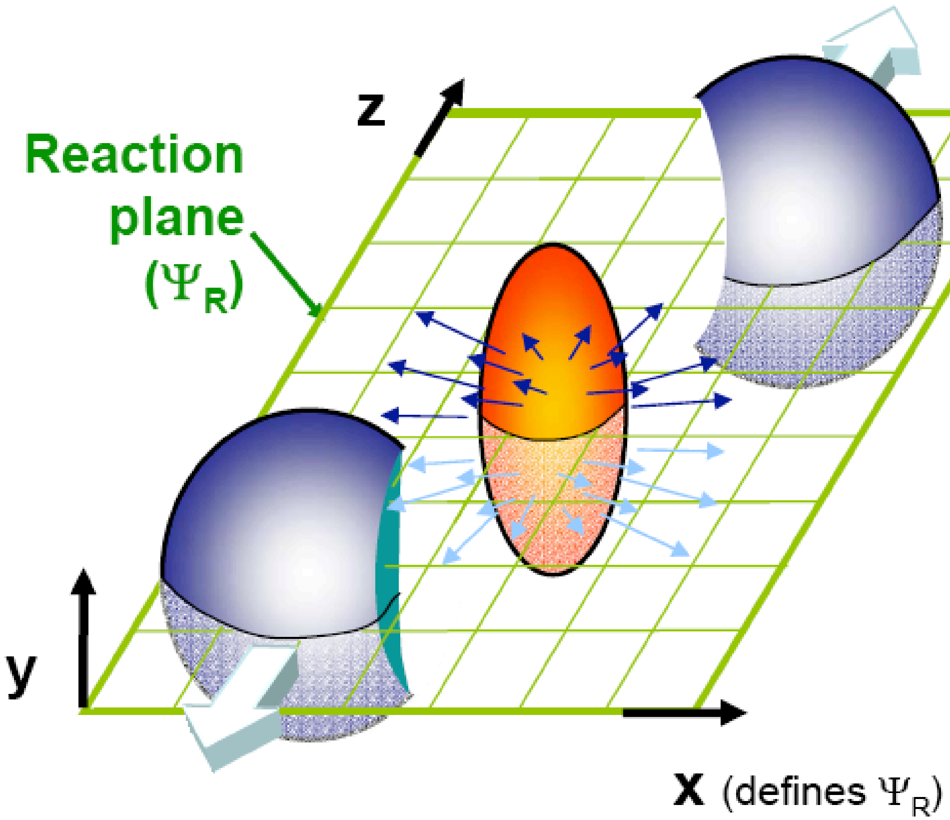
What have we learned from RHIC so far ?

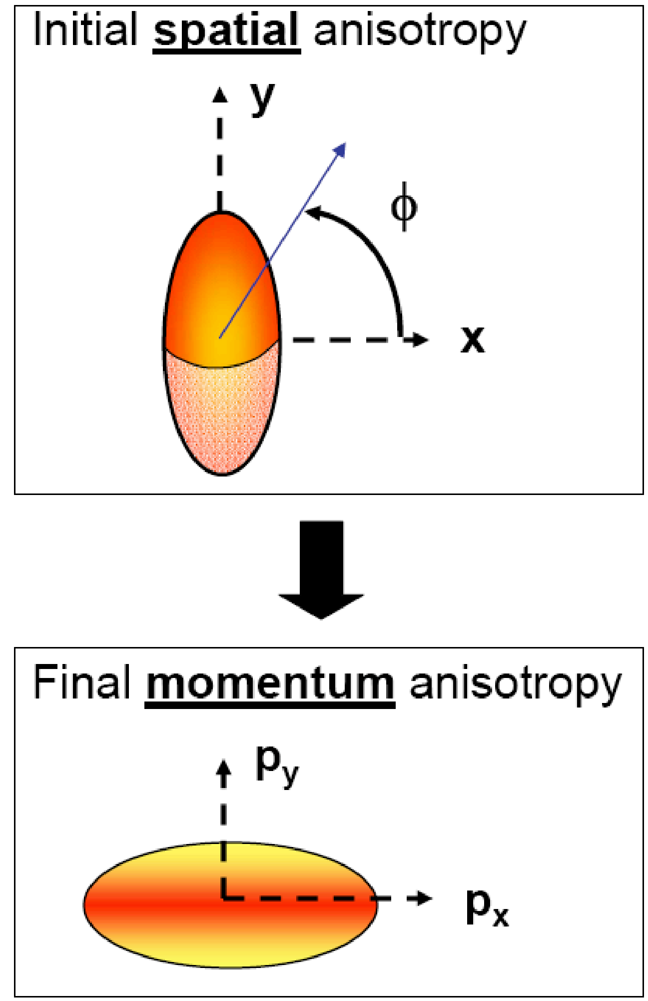
I. Collective flow =>
Au-Au collisions at RHIC produce strongly interacting matter





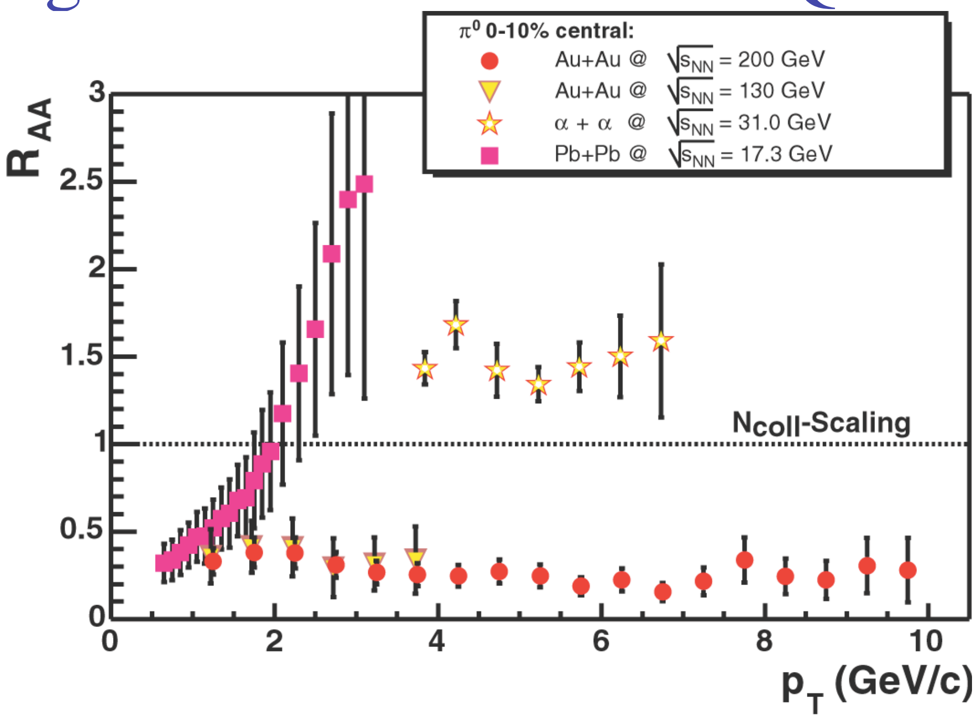
Azimuthal anisotropy defined

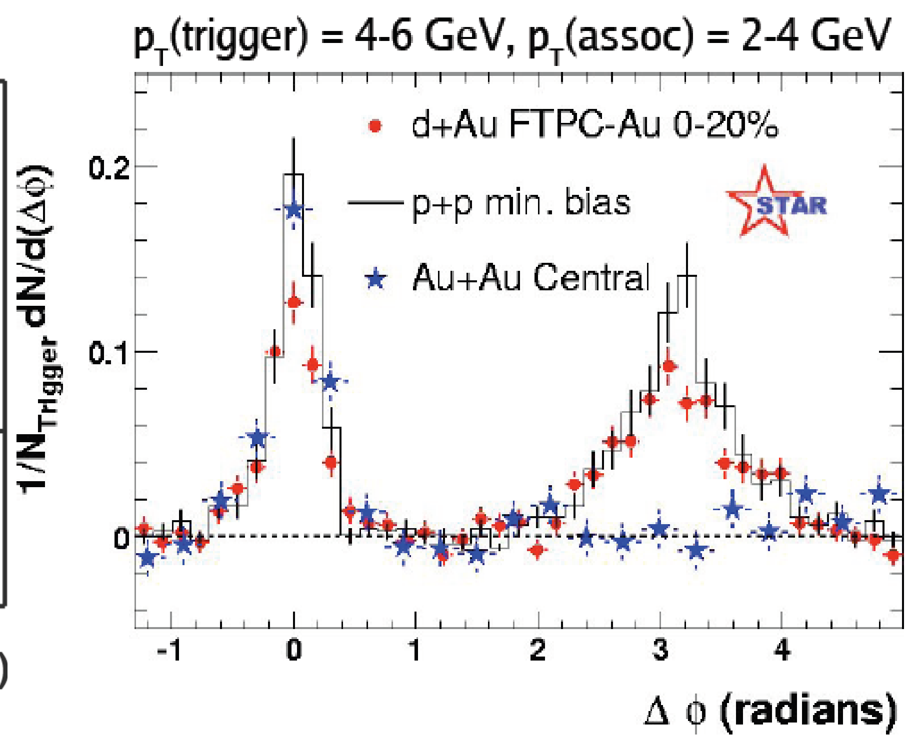




What have we learned from RHIC so far ?

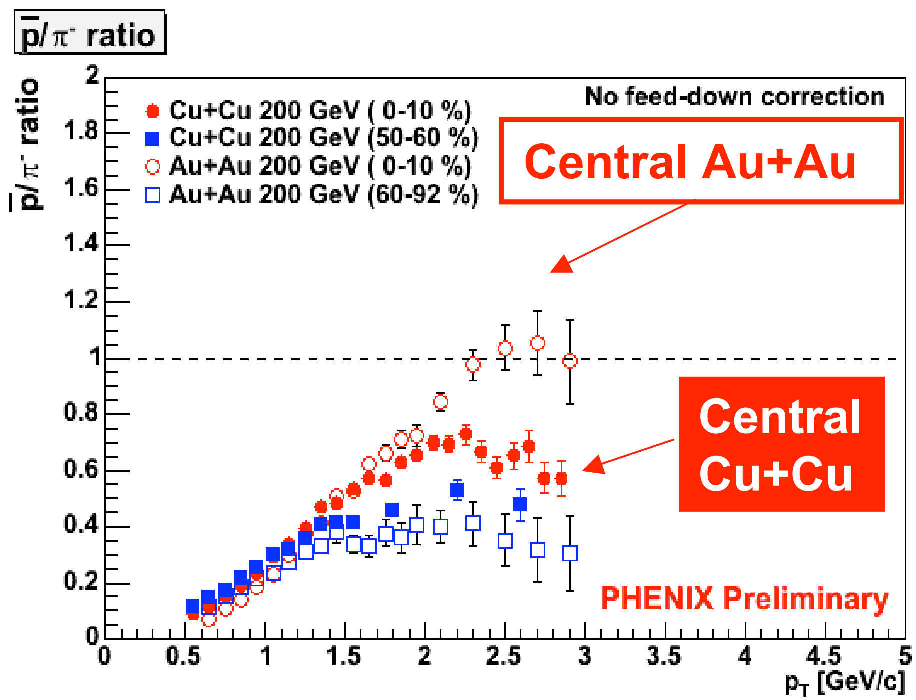
II. Suppression of high p_T particles =>
consistent with the predicted jet energy loss from induced gluon radiation in dense QCD matter

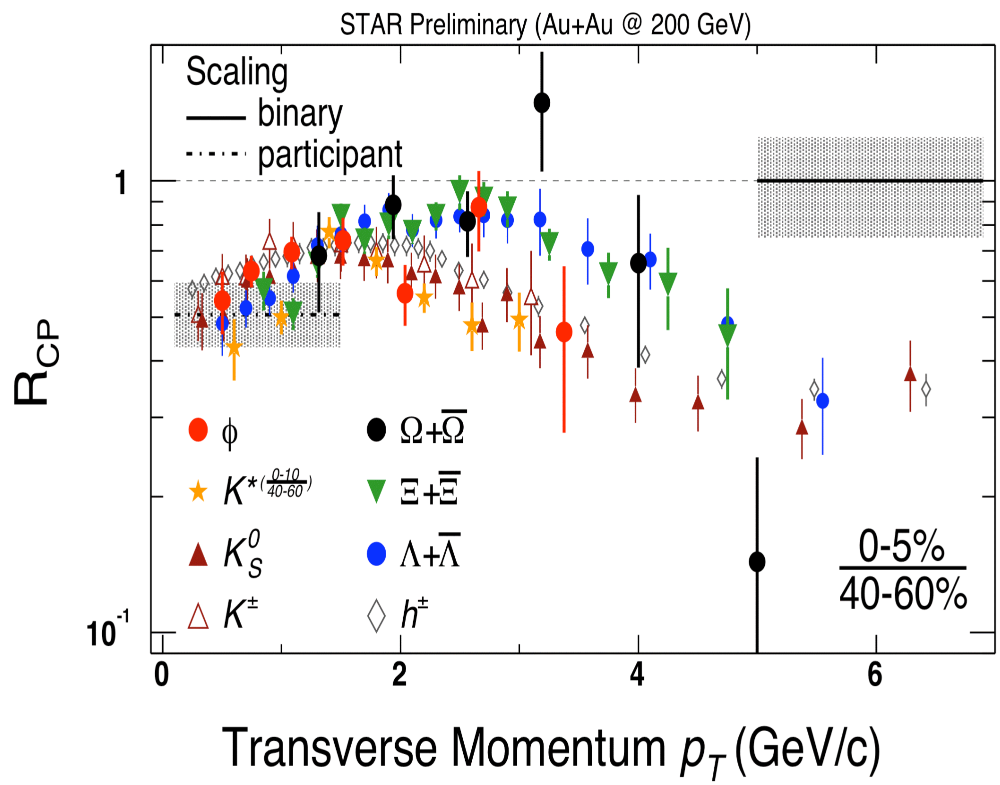




What have we learned from RHIC so far ?

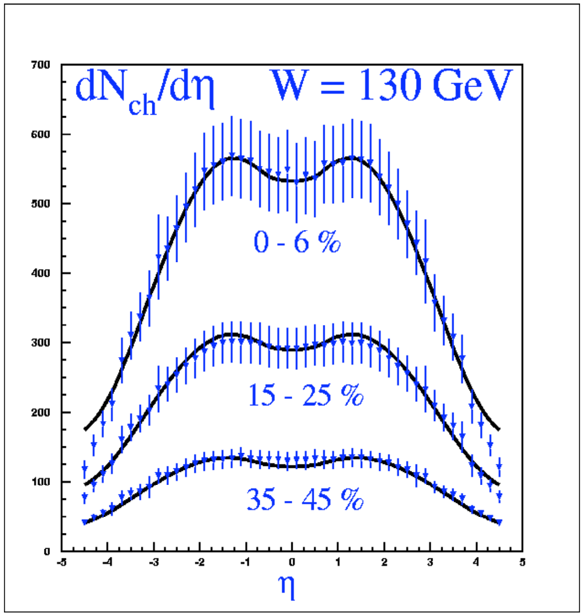
III. Baryon/meson enhancement =>
Constituent quark recombination? Baryon junctions?

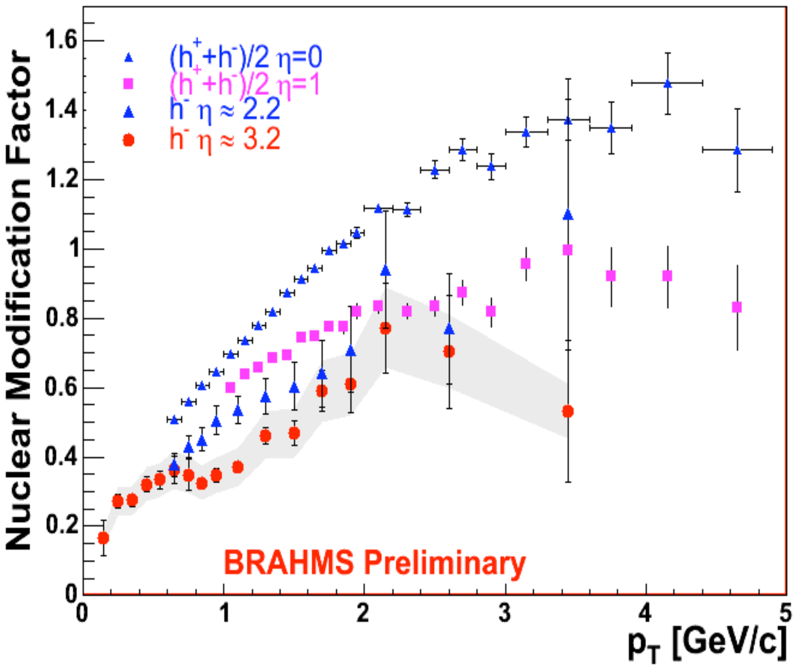




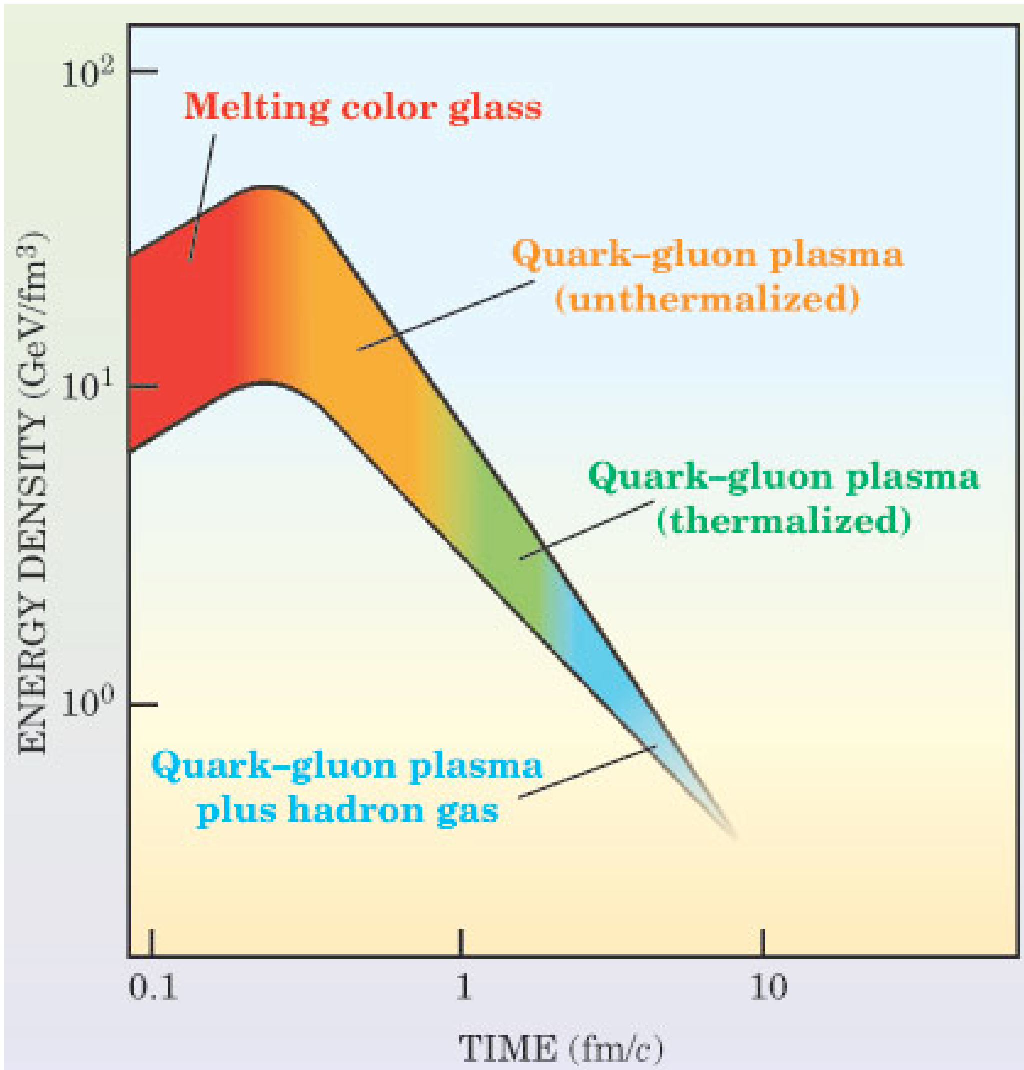
What have we learned from RHIC so far ?

IV. "Small" hadron multiplicities +
suppression of high p_T particles at forward rapidities =>
coherent interactions in the initial state, consistent
with the presence of parton saturation/Color Glass Condensate





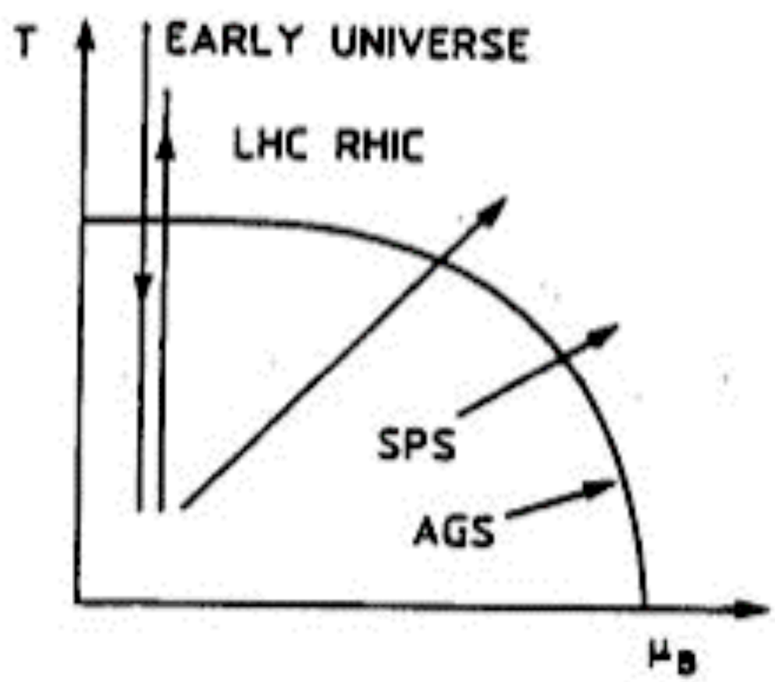
The emerging picture

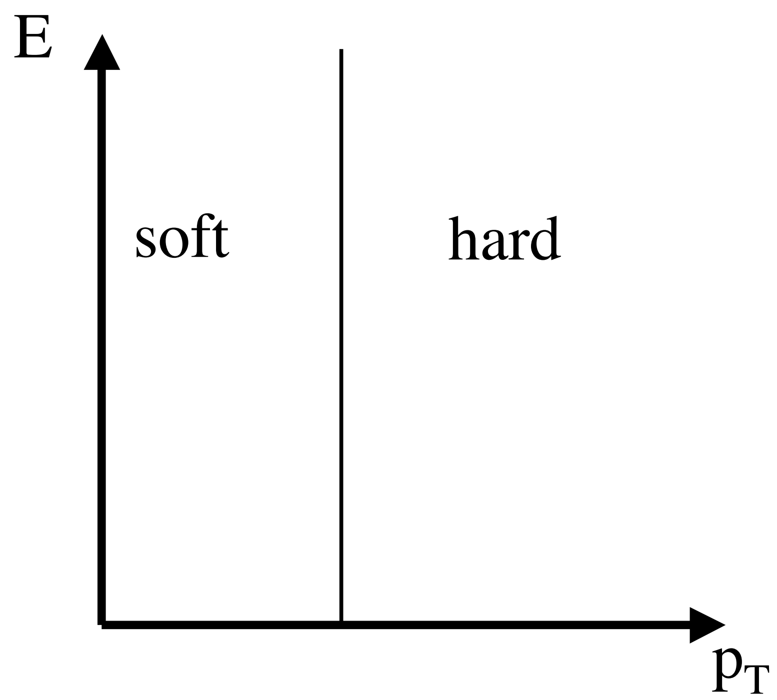


Why is thermalization so fast?

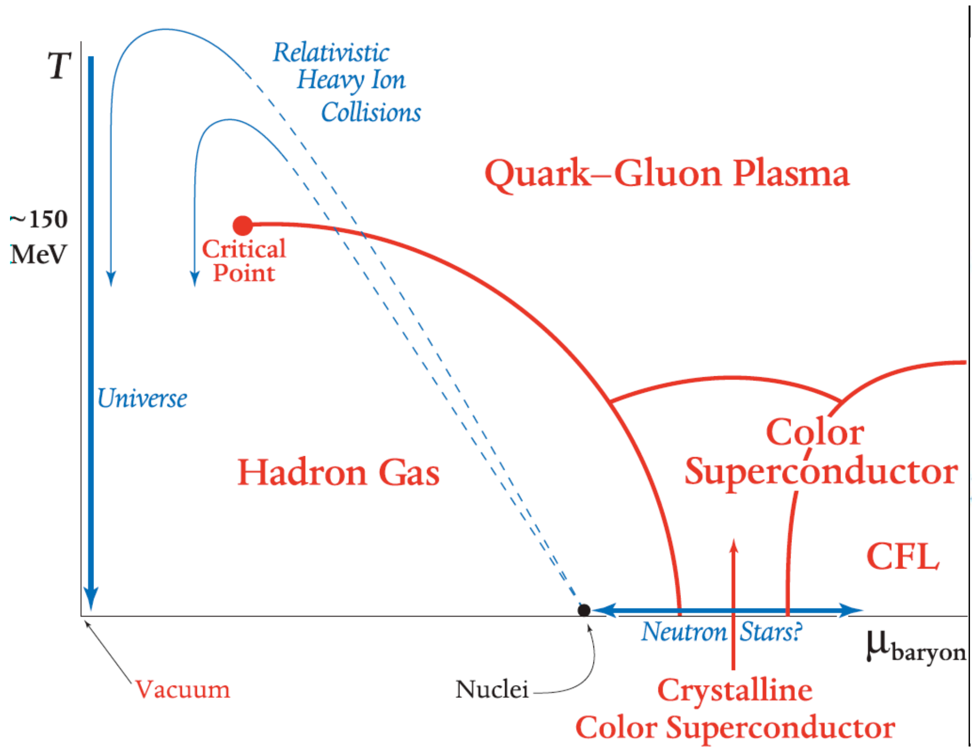
T. Ludlam,
L. McLerran,
Physics Today
October 2003

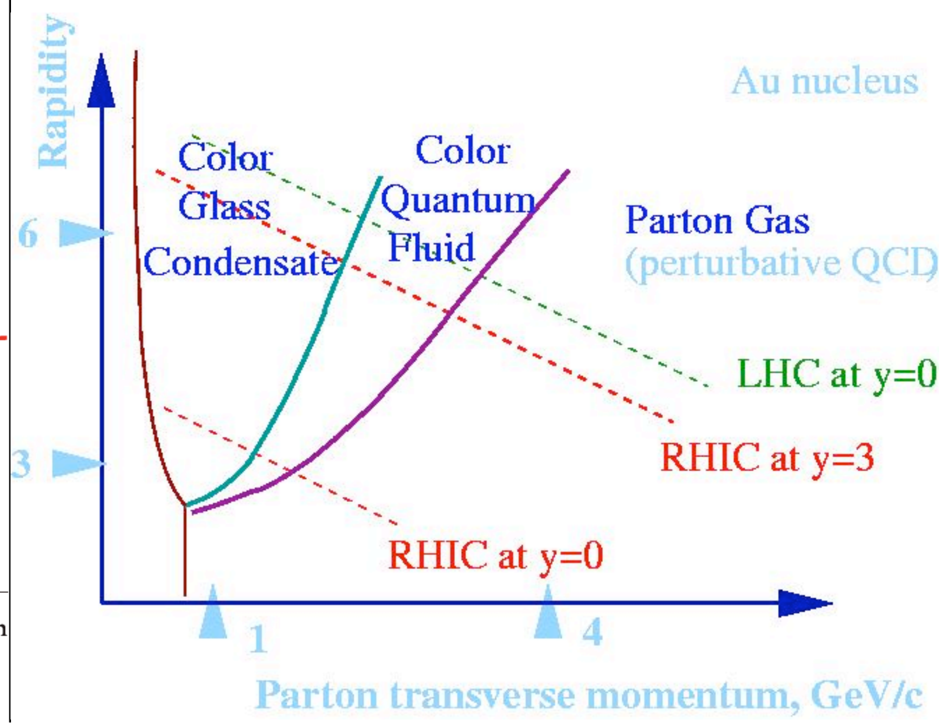
QCD diagrams, late XX century



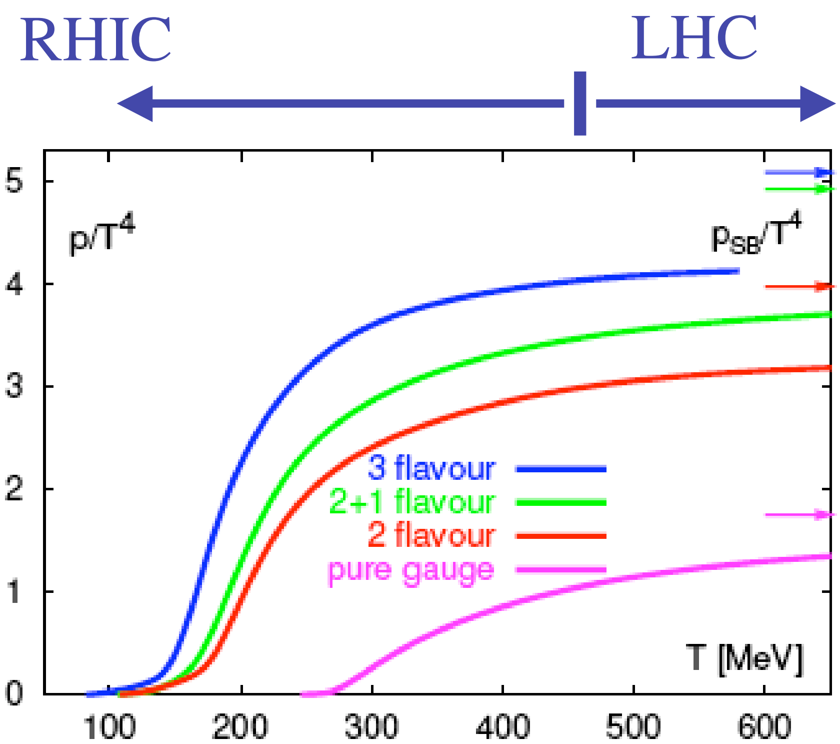


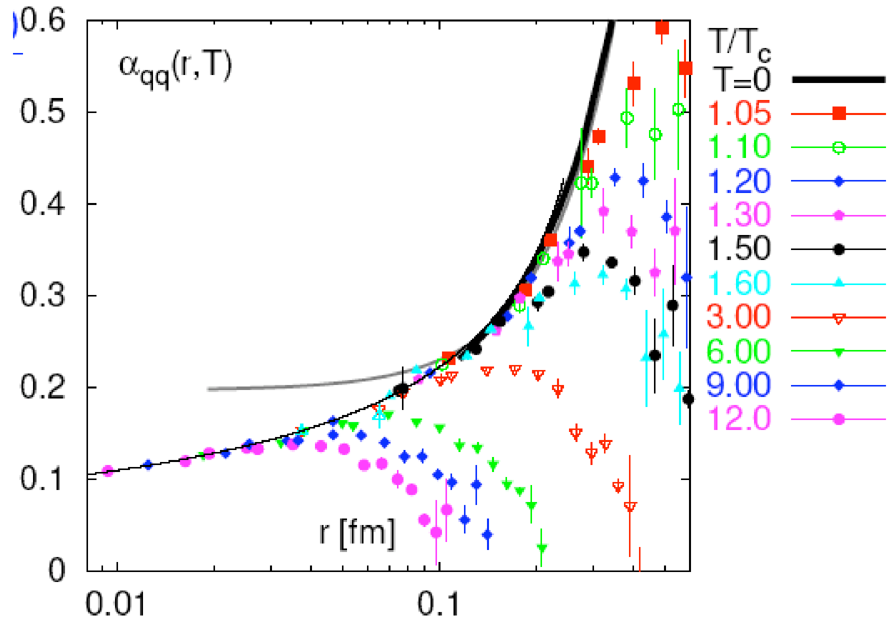
QCD diagrams, early XXI century





Strongly coupled QGP



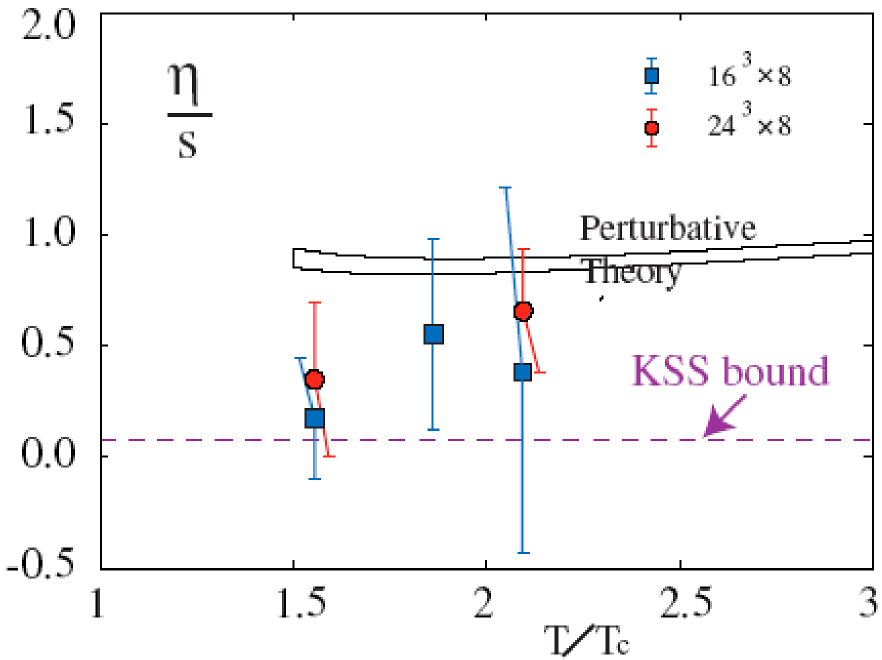


$$\epsilon \neq 3P$$

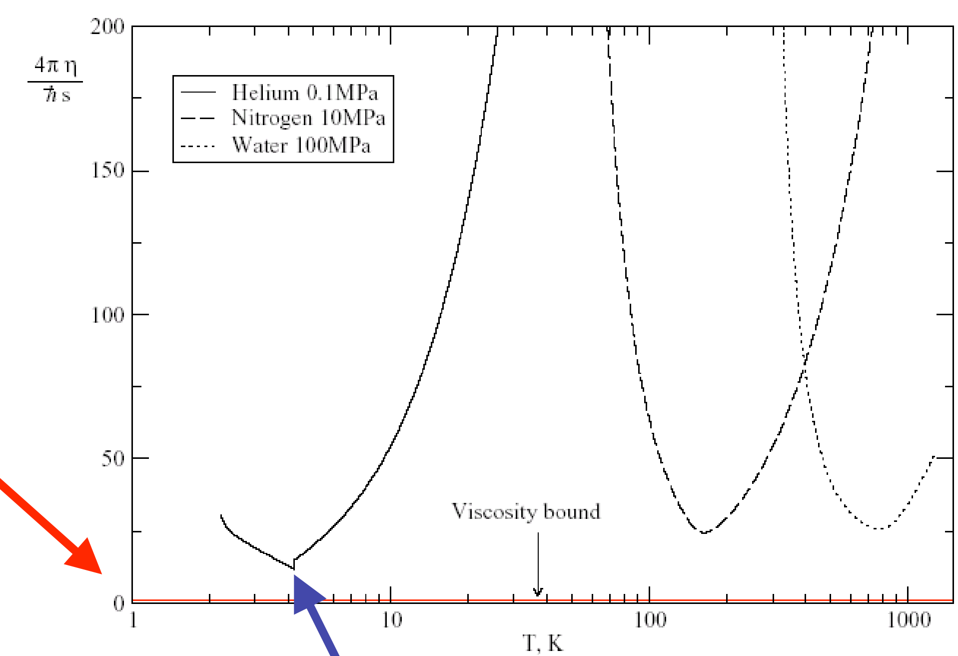
F. Karsch et al

T-dependence of the running coupling develops in the NP-region at T < 3 T_c

sQGP: more fluid than water?



A.Nakamura and S.Sakai,
hep-lat/0406009



Superfluid helium

KSS bound:
strongly coupled SUSY QCD = classical supergravity

What do we still need to know?

1. What are the dynamical degrees of freedom in sQGP and CGC?

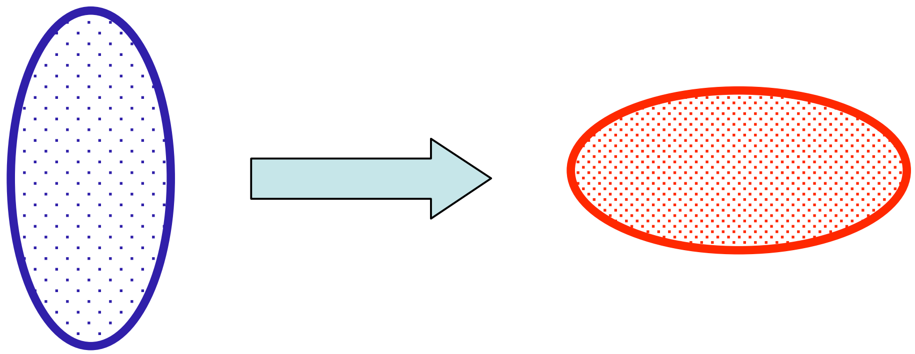
2. How does the transition from CGC to sQGP occur?

3. How does the sQGP interact with the hard probes?

4. How does sQGP hadronize?

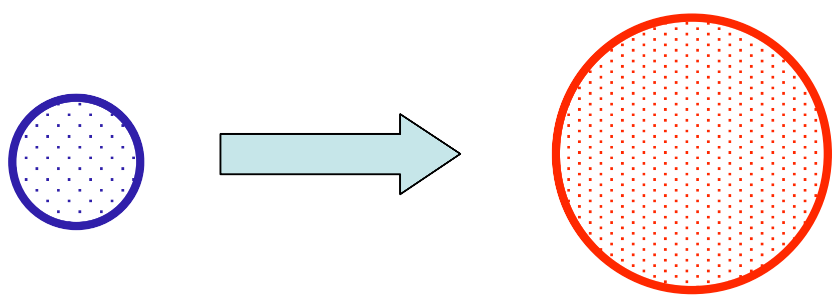
Recent development: bulk viscosity

Shear viscosity: how much entropy is produced by transformation of shape at constant volume



Generated by translations

Bulk viscosity: how much entropy is produced by transformation of volume at constant shape



Generated by dilatations

Shear and bulk viscosities: the definitions

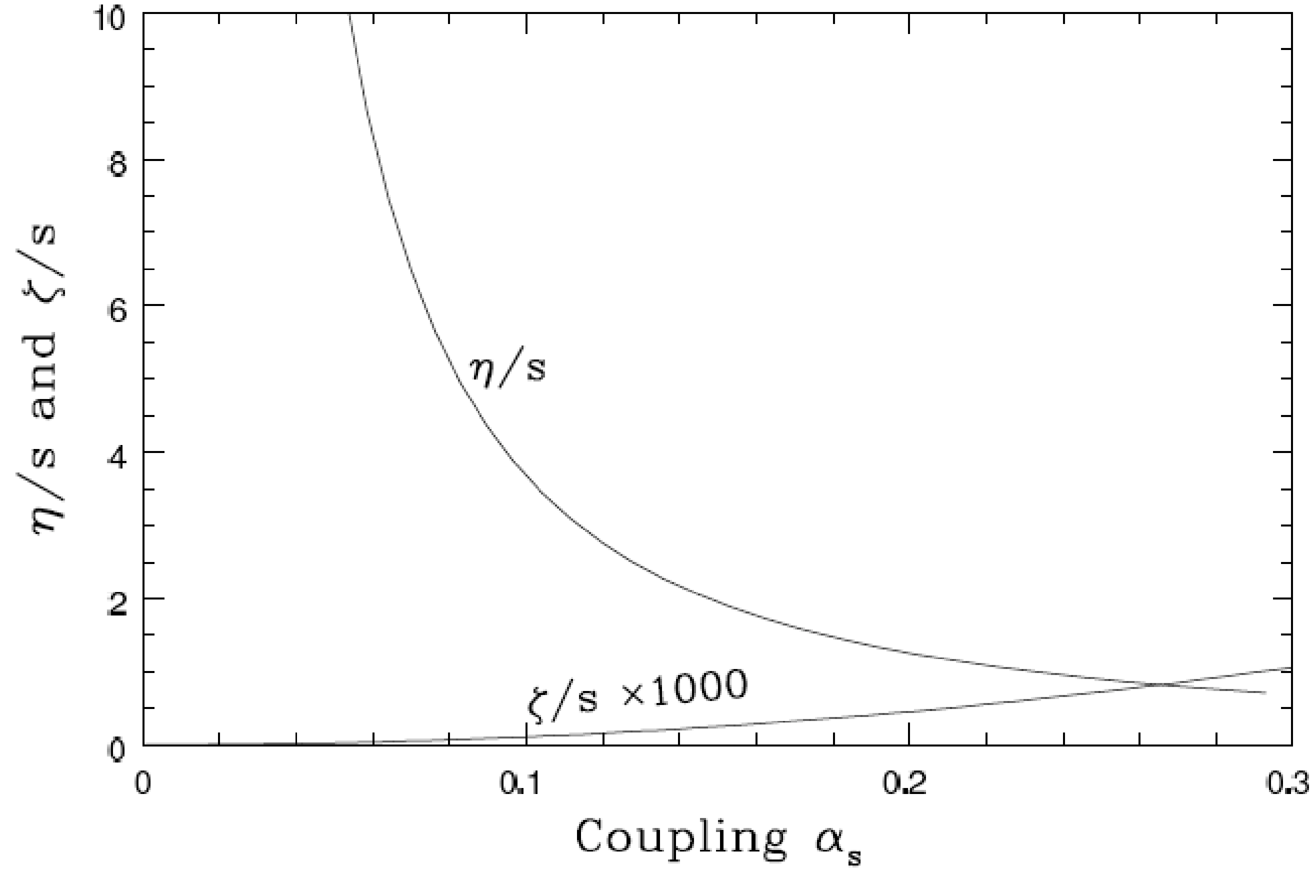
The energy-momentum tensor:

$$\theta_{ij} = P_{eq}(\epsilon)\delta_{ij} - \eta\ \left(\partial_i u_j + \partial_j u_i - \frac{2}{3}\delta_{ij}\partial_k u_k\right) - \zeta\ \delta_{ij}\vec{\nabla}\cdot\vec{u}$$

shear viscosity

bulk viscosity

Perturbation theory: bulk viscosity is negligibly small



$\zeta/\eta < 10^{-3}$

$$\zeta \sim \frac{\alpha_s^2 T^3}{\log[1/\alpha_s]} \quad (m_0 \ll \alpha_s T)$$

P.Arnold, C.Dogan, G.Moore, hep-ph/0608012

In perturbation theory, shear viscosity is “large”:

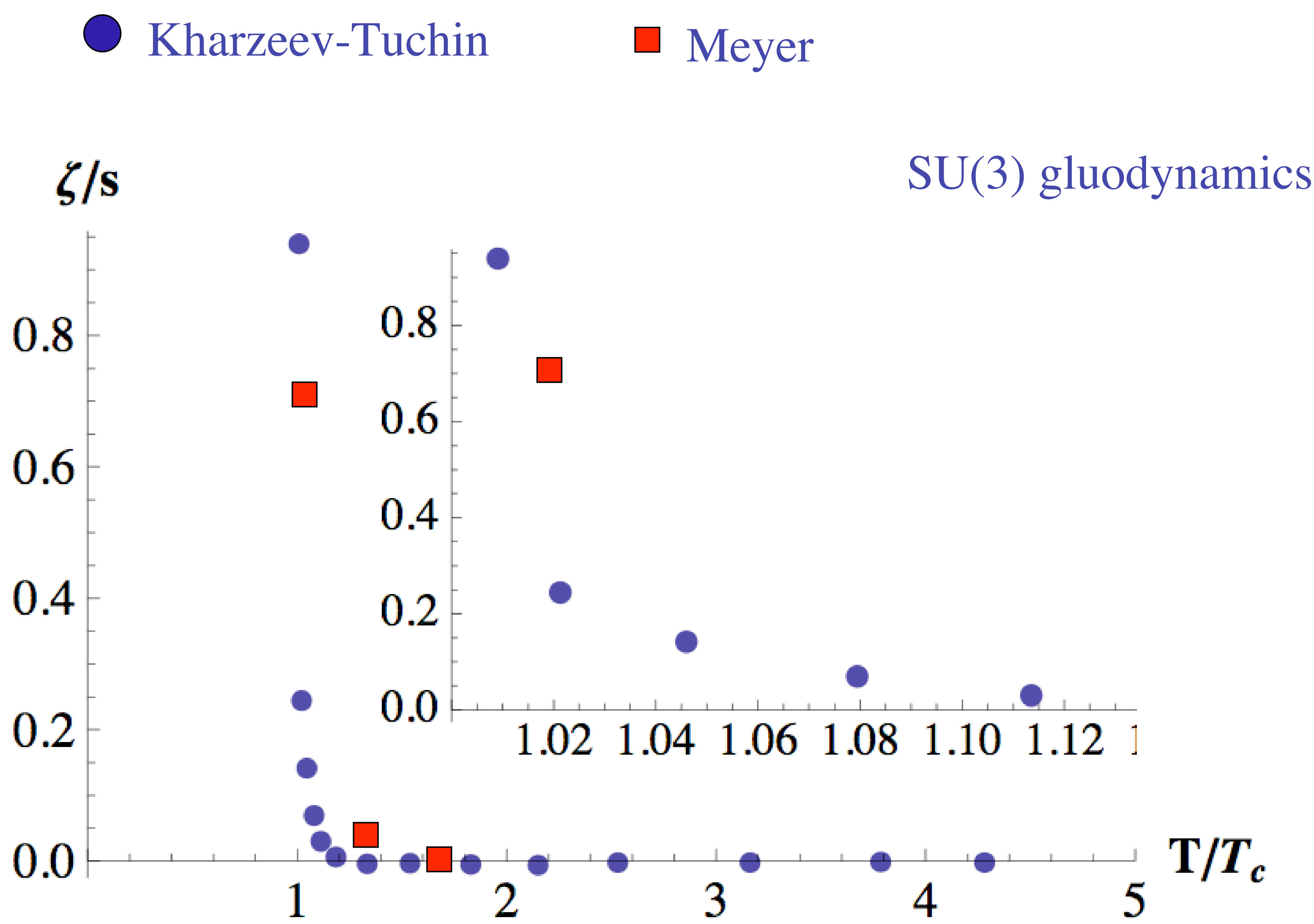
$$\frac{\eta}{s} \sim \frac{1}{\alpha_s^2}$$

and bulk viscosity is “small”:

$$\frac{\zeta}{s} \sim \alpha_s^2$$

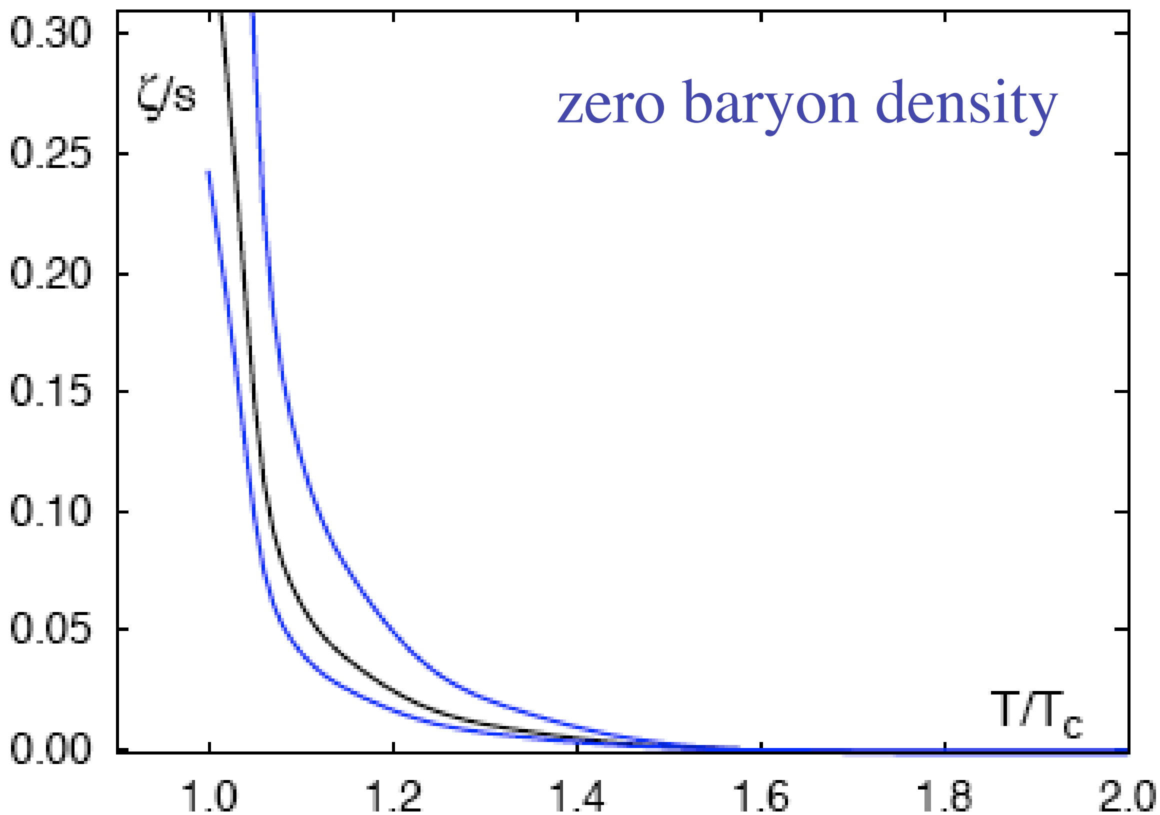
At strong coupling, η is apparently small;

can ζ get large?



DK, K. Tuchin, arXiv:0705.4280;   H. Meyer, arXiv:0710.3717;

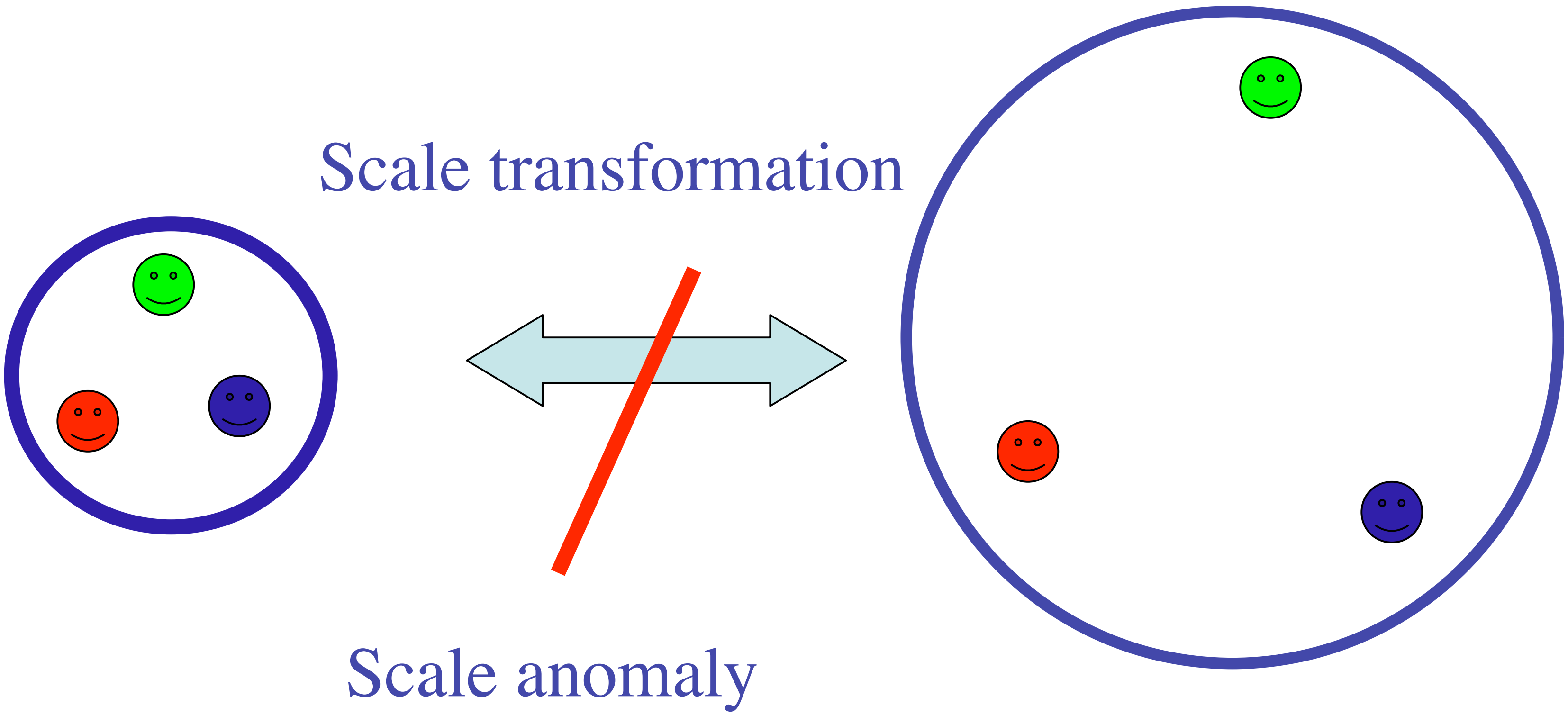
2+1 light quarks, "real" QCD



F. Karsch, DK, K. Tuchin, arXiv:0711.0914

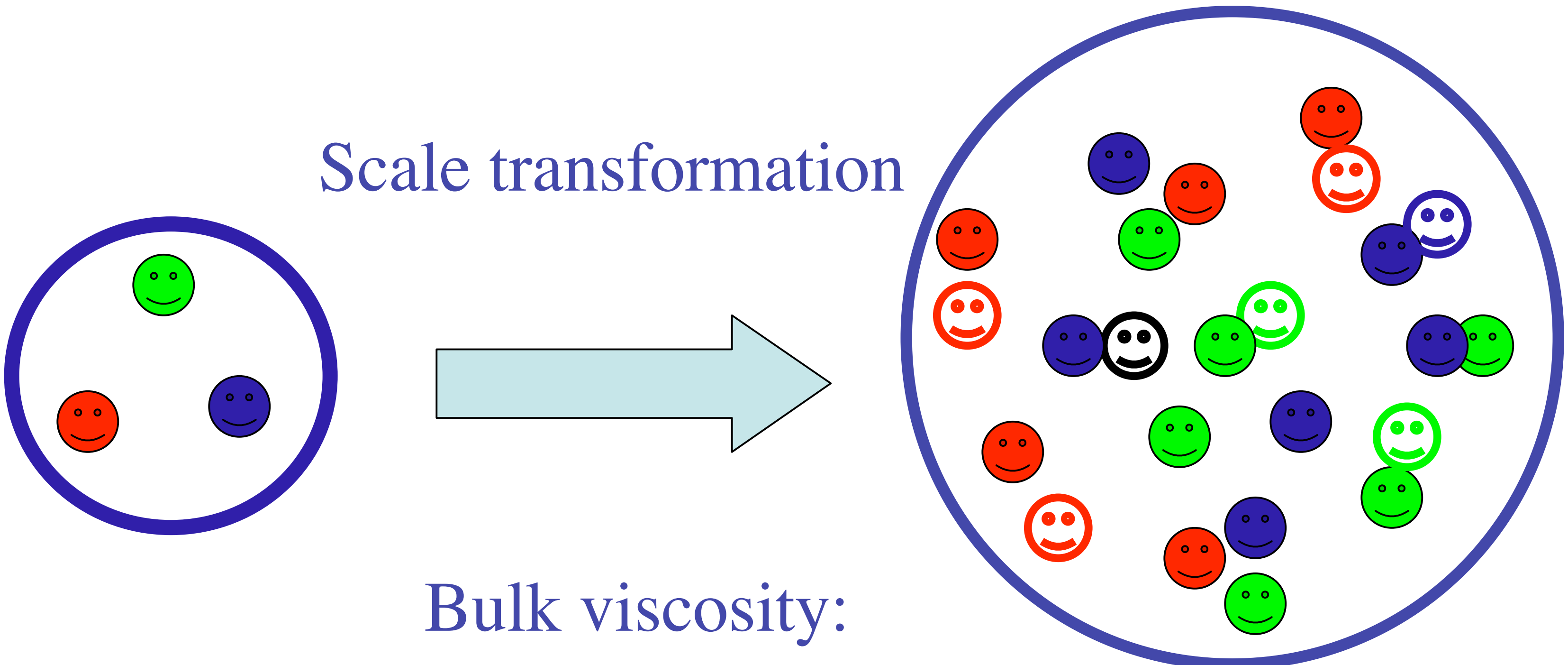
+ Bulk viscosity diverges near the chiral critical point -
large entropy production, high multiplicity, small average p_T

Bulk viscosity and the mechanism of hadronization



What is the meaning of the bulk viscosity growth?

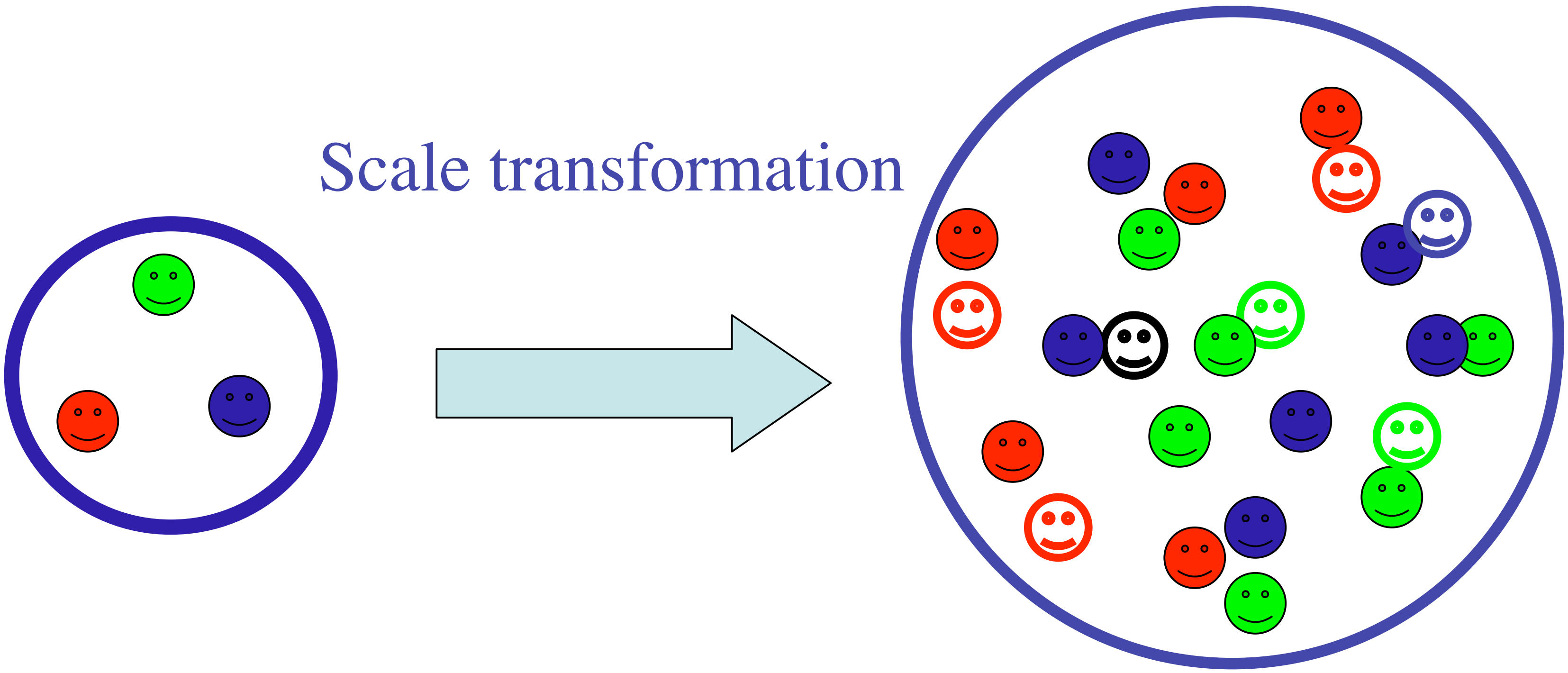
Bulk viscosity and the mechanism of hadronization



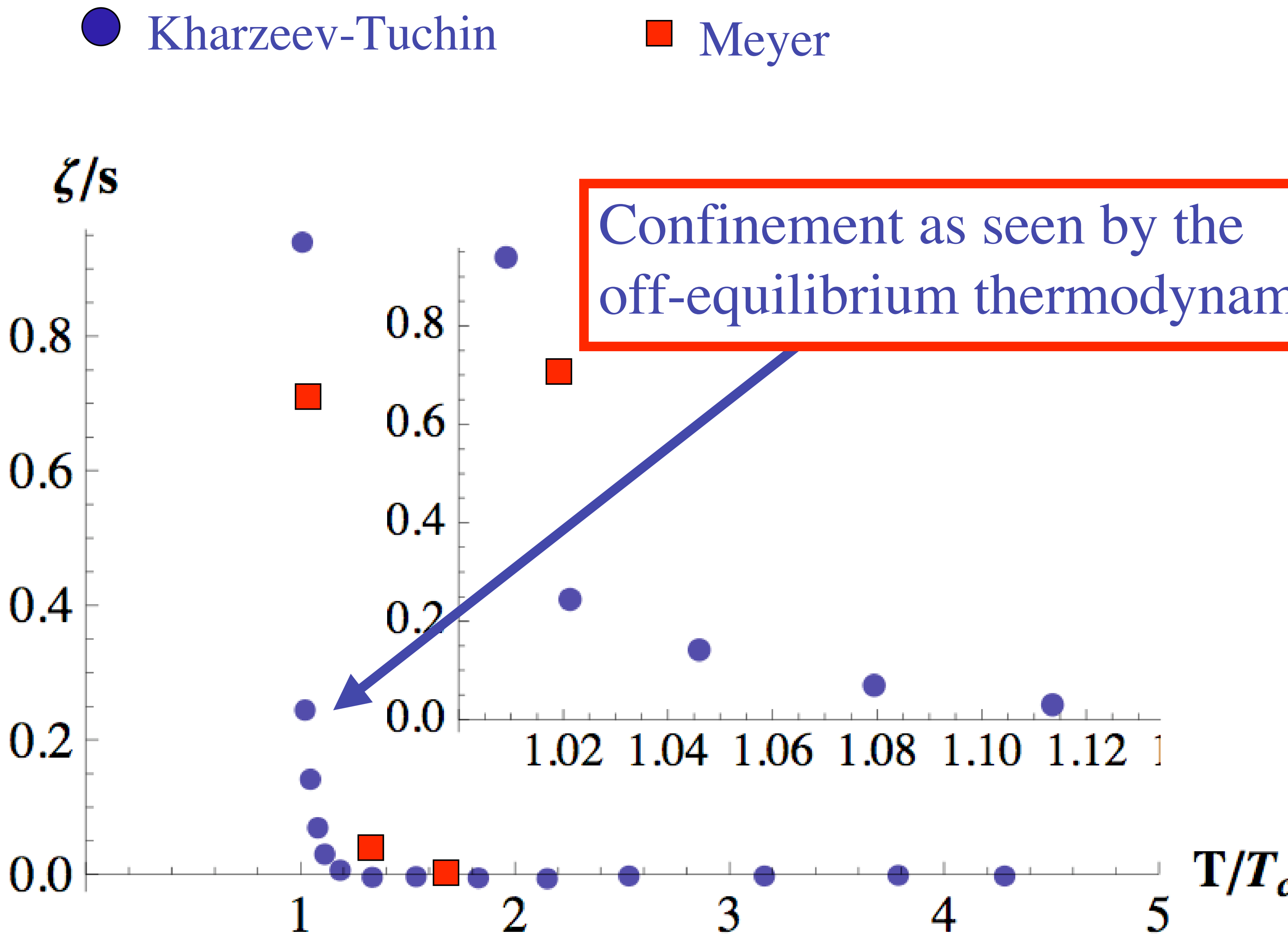
Bulk viscosity:
growth of entropy,
particle production

Bulk viscosity growth = soft statistical hadronization (?)

Bulk viscosity and the mechanism of hadronization



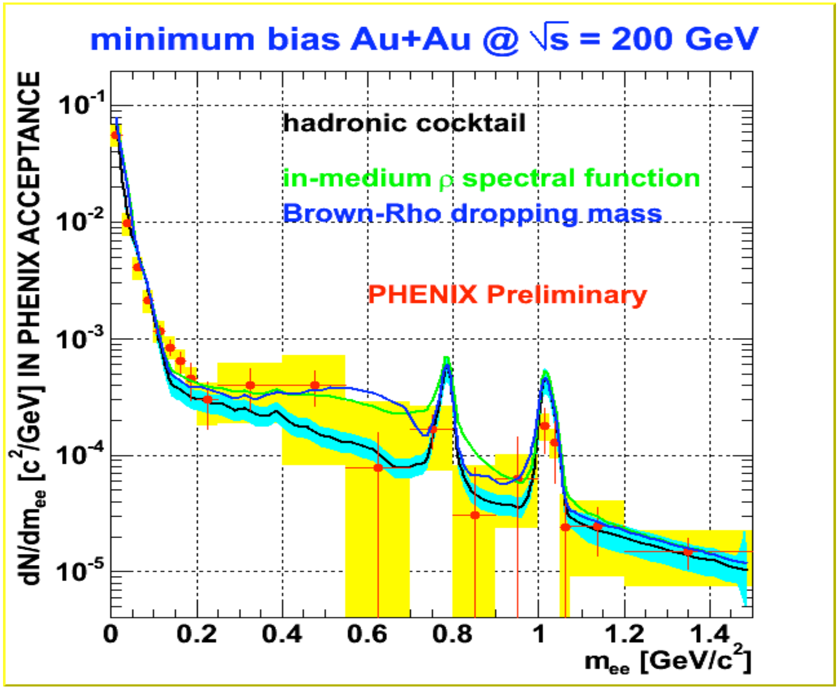
<u>Not</u> a recombination of pre-existing quarks -
Bulk viscosity saves the 2nd law of thermodynamics
in the process of hadronization;
Easier to produce baryons? B/π enhancement?



Kharzeev-Tuchin
Meyer
ζ/s
Confinement as seen by the
off-equilibrium thermodynamics
0.8
0.6
0.4
0.2
0.0
1.02
1.04
1.06
1.08
1.10
1.12
1
2
3
4
5
T/Tc

What are the dynamical degrees of freedom in sQGP?

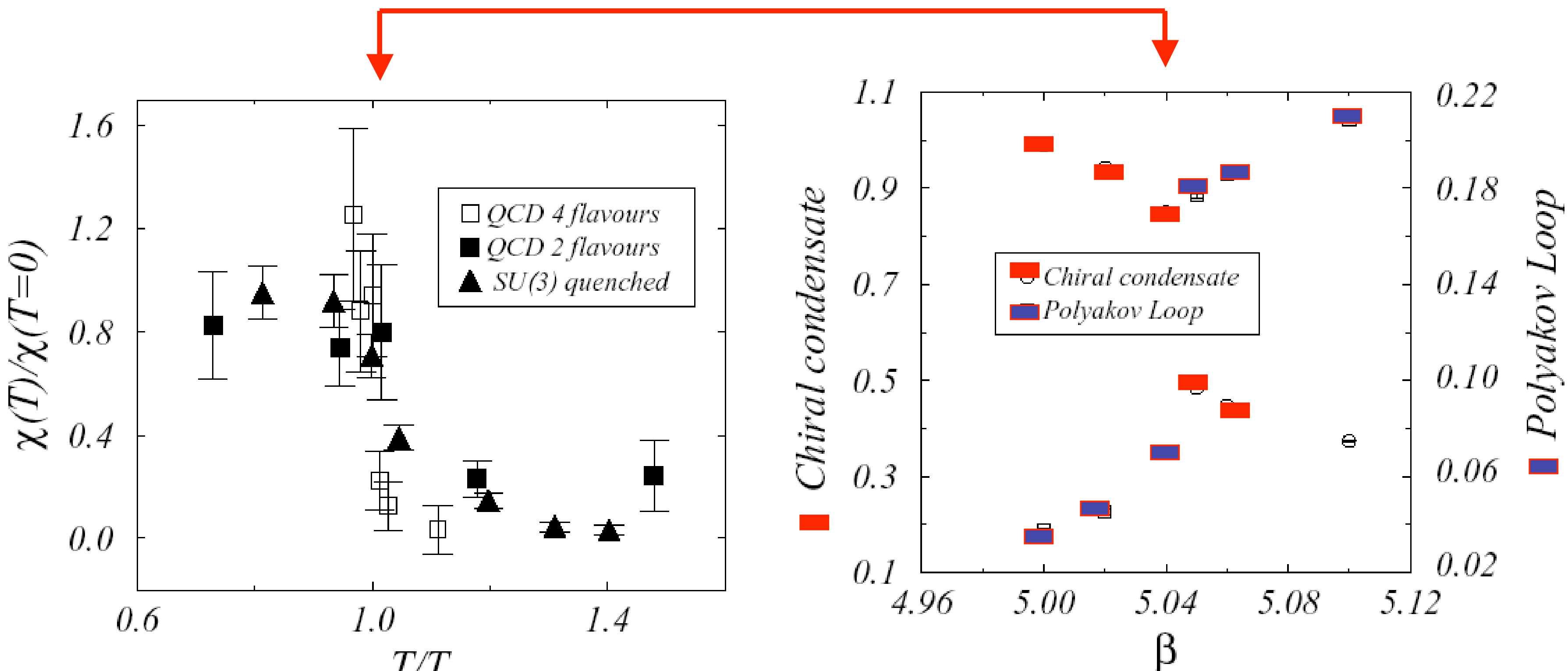
What is the fate of the chiral symmetry in dense QCD matter?



Spontaneous chiral symmetry breaking mixes left-and right-handed quarks and generates their masses (analogous to Cooper pair condensate in a superconductor)

At high temperature, the condensate can be destroyed - Measure the mass spectra of vector and axial-vector quark-antiquark current through low-mass dileptons and $\gamma\pi$

The flavor-singlet part of chiral symmetry: $U_A(1)$ - “left” vs “right”

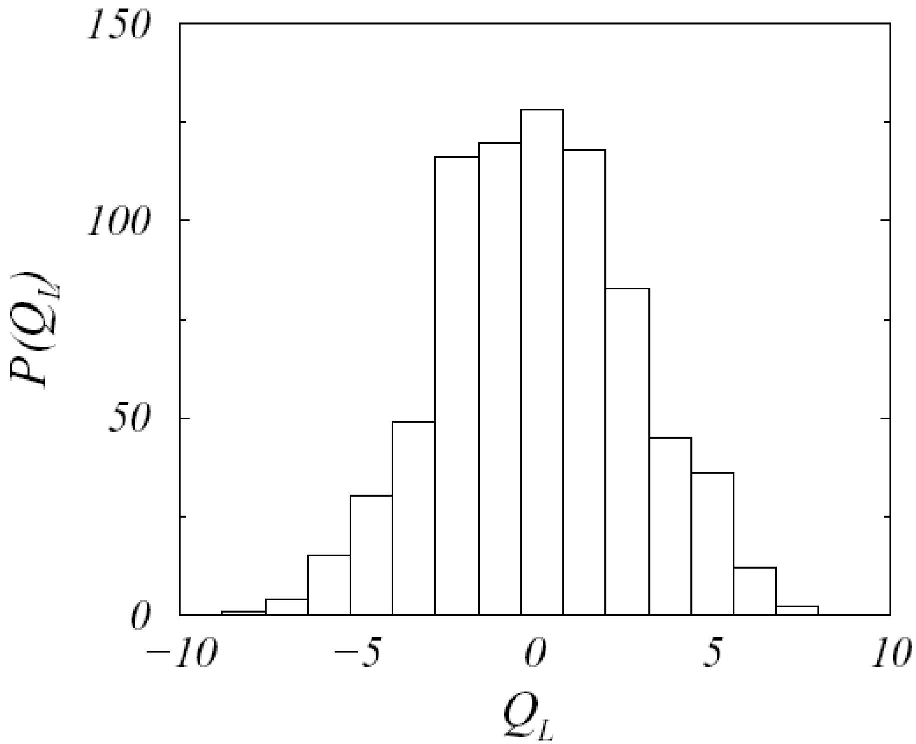


$$\langle L \rangle \sim exp(-E_q/T)$$

Rapid decrease of susceptibility at the deconfinement phase transition

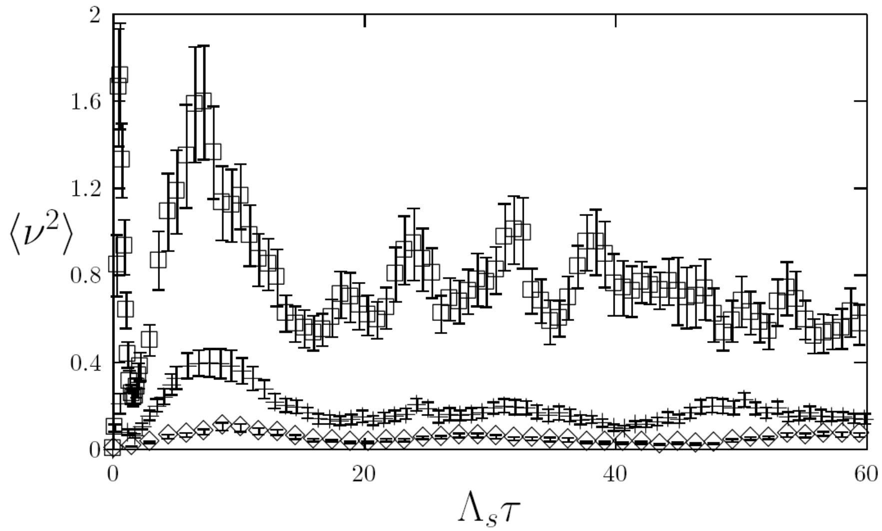
B.Alles, M.D’Elia and A.DiGiacomo, hep-lat/0004020

Fluctuations of Chern-Simons number in hot QCD: numerical lattice simulations

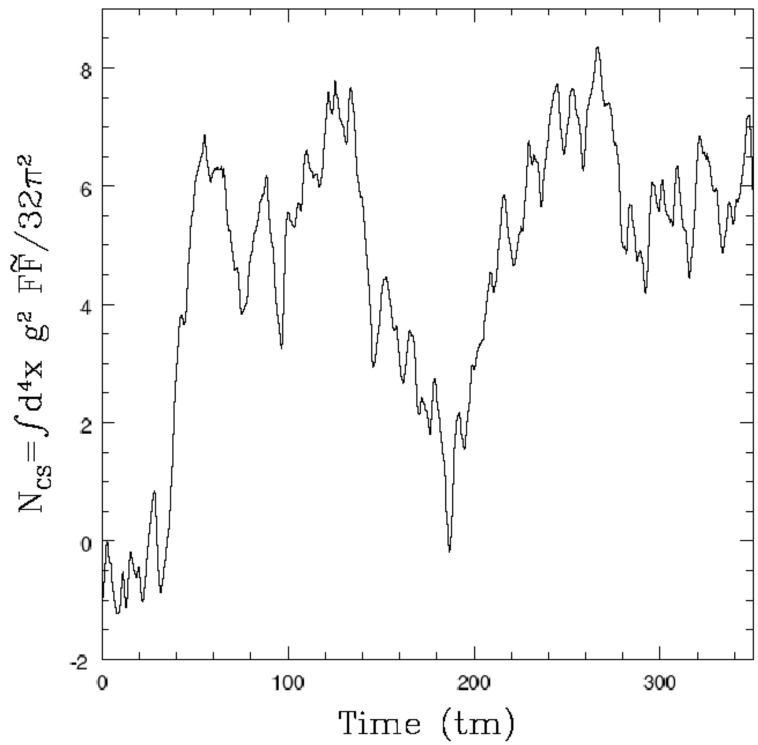


B.Alles, M.D'Elia and A.DiGiacomo, hep-lat/0004020

Diffusion of Chern-Simons number in QCD: real time lattice simulations



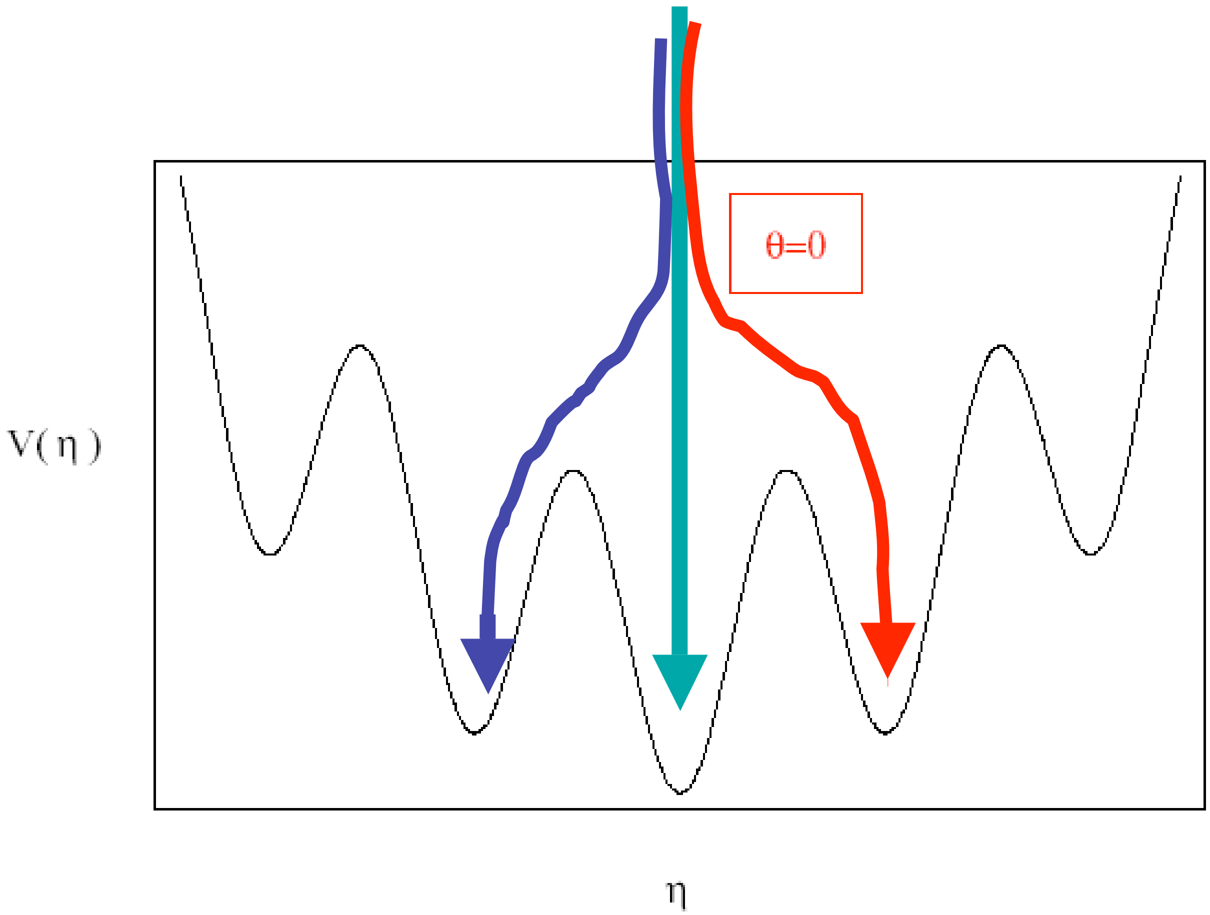
DK, A.Krasnitz and R.Venugopalan,
Phys.Lett.B545:298-306,2002



P.Arnold and G.Moore,
Phys.Rev.D73:025006,2006

What are the experimental signatures?

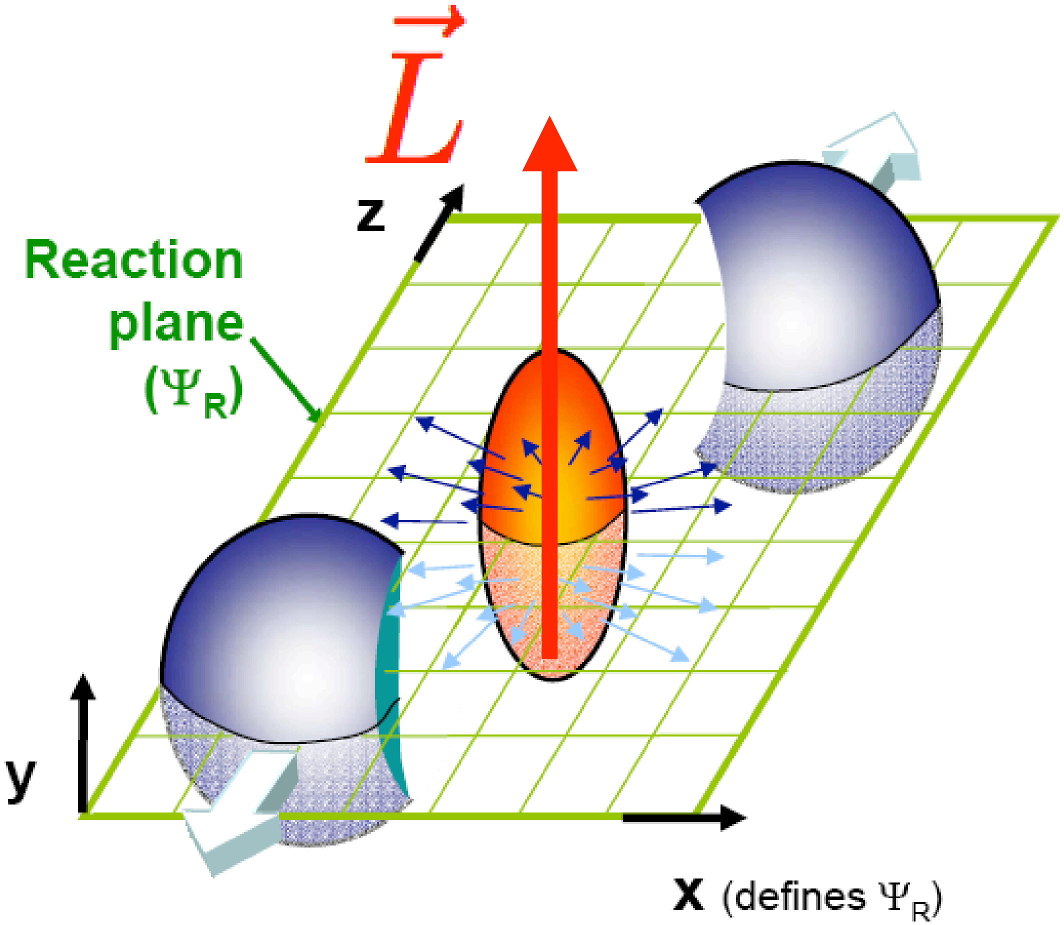
CP-odd domains in heavy ion collisions: how to look for them?



Similar to DCC

v.e.v. of the η field is equivalent to non-zero θ

Azimuthal anisotropy = angular momentum

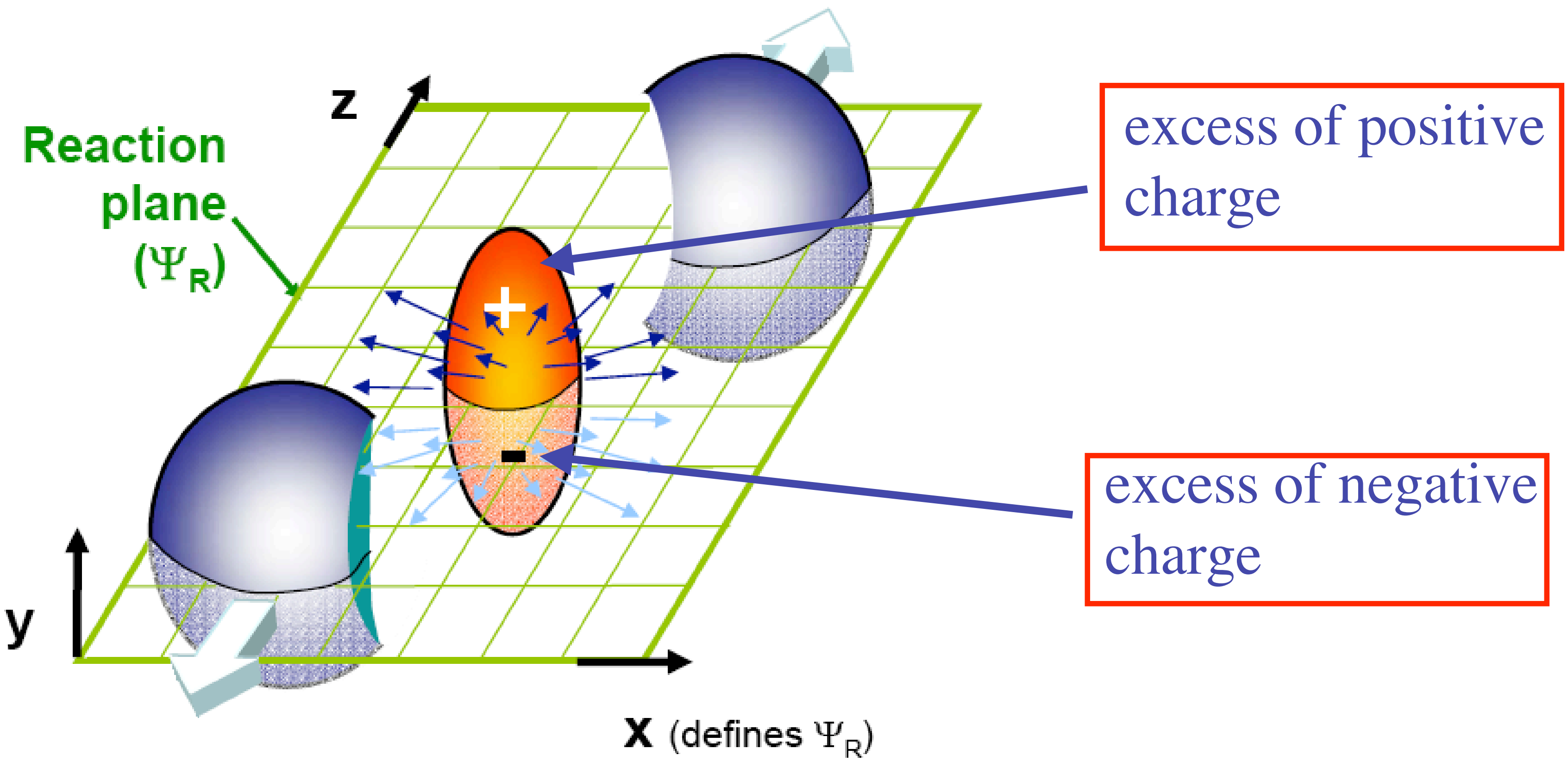


Strong magnetic field:

DK, L. McLerran, H. Warringa, arXiv:0711.0950

(Effect on dileptons? Loss of back-to-back correlations?)

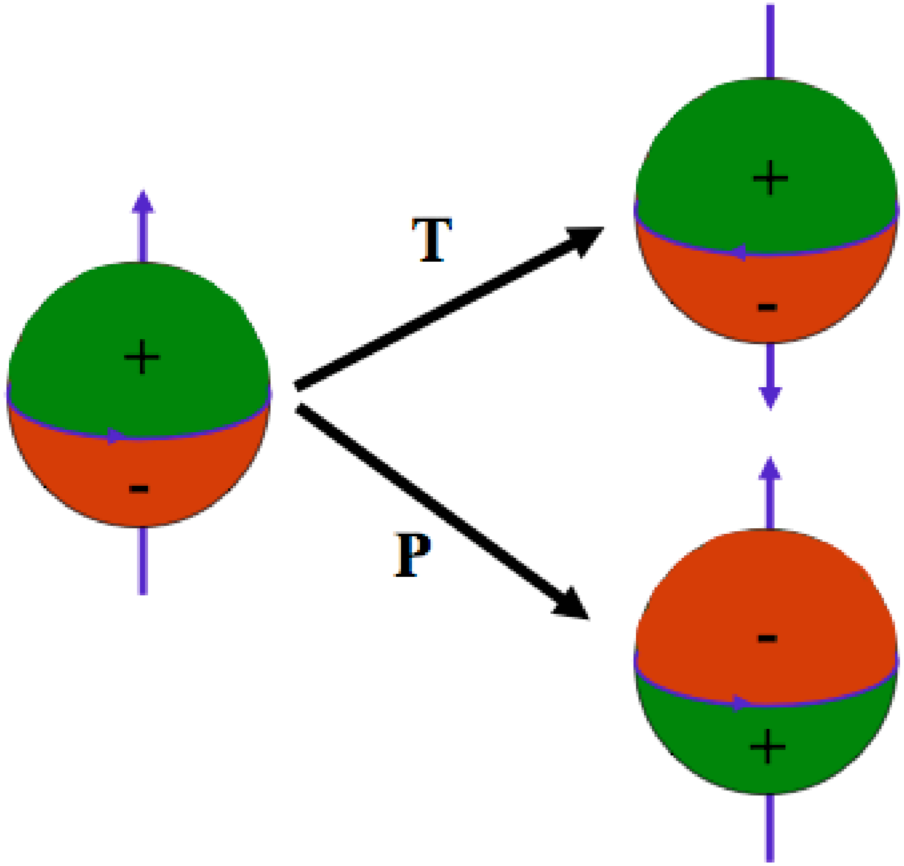
Charge asymmetry w.r.t. reaction plane as a signature of strong CP violation



Electric dipole moment of QCD matter!

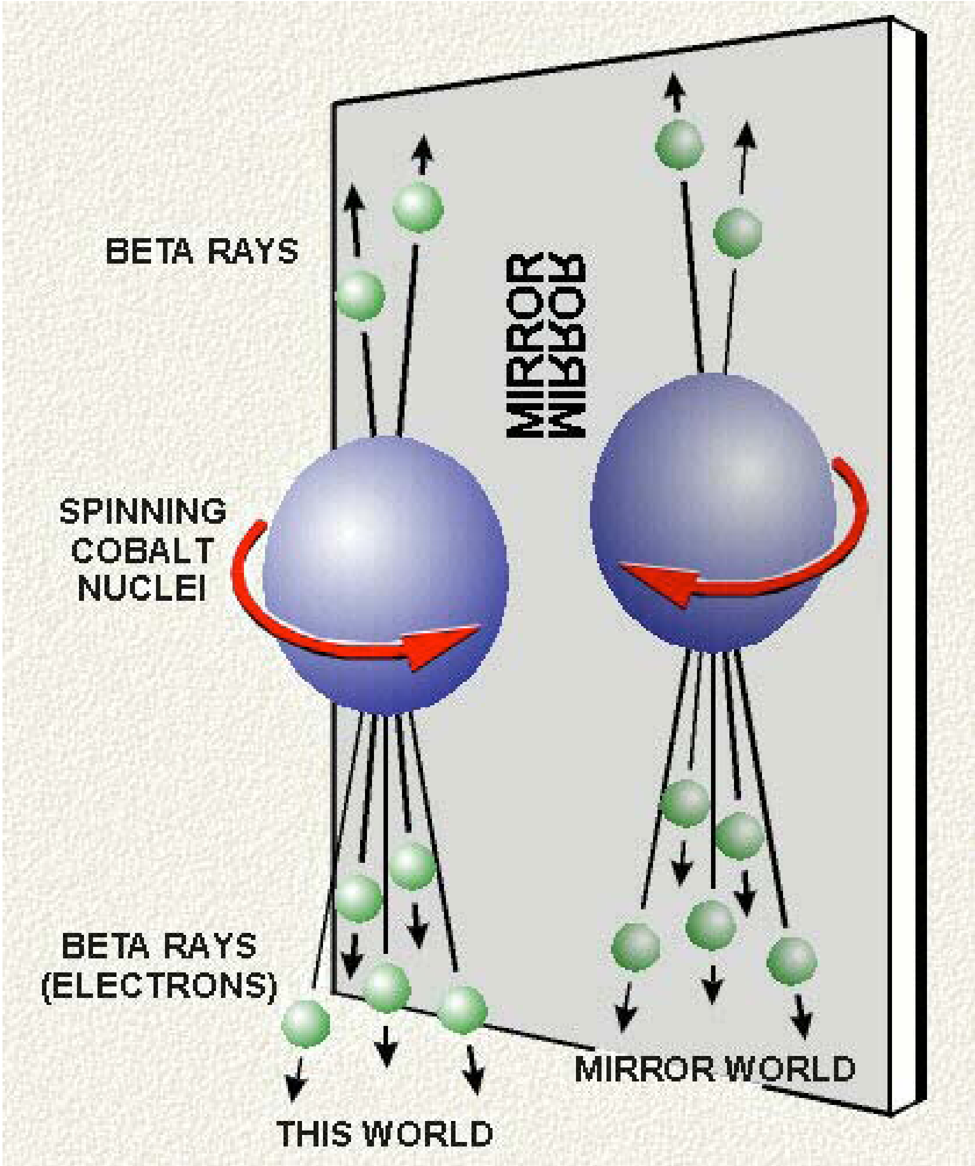
DK, hep-ph/0406125

Charge asymmetry w. r.t. reaction plane violates T, P, and (by CPT theorem) CP:

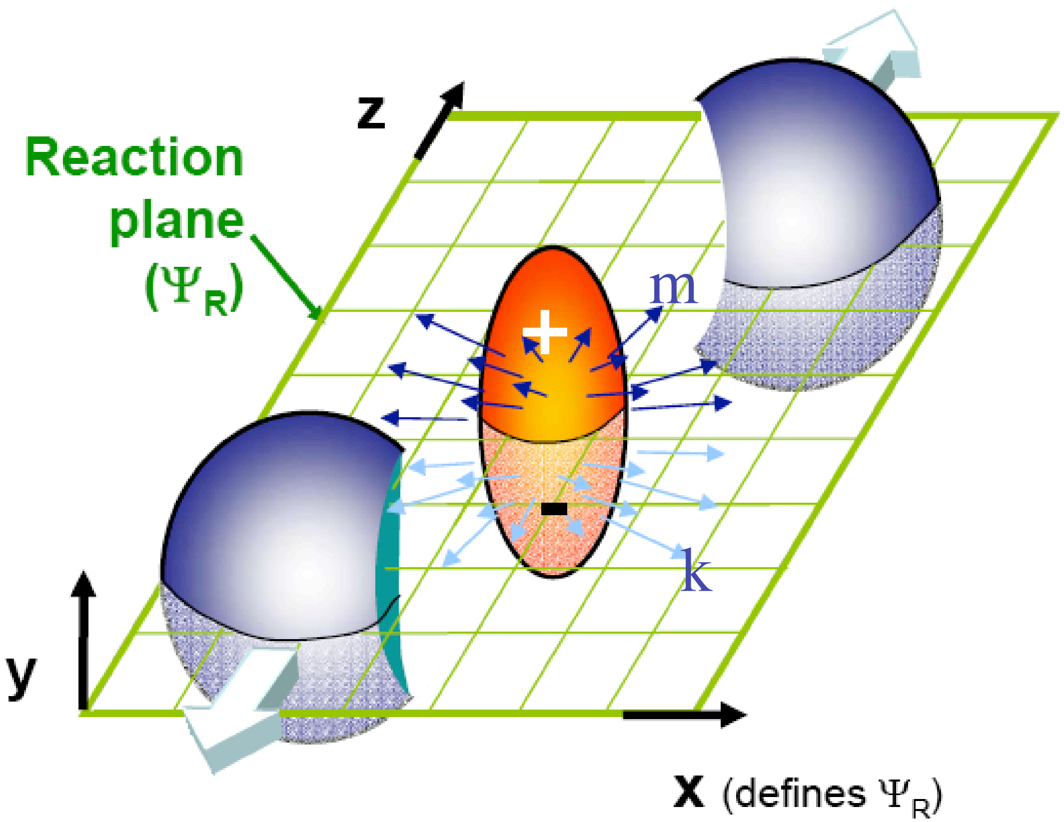


Recent theory developments:
DK, A.Zhitnitsky, arXiv:0706.1026;
DK, L. McLerran, H. Warringa, arXiv:0711.0950

Analogy to P violation in weak interactions



Charge asymmetry w.r.t. reaction plane: how to detect it?



We need
a sensitive measure
of the asymmetry

Improved method:
"mixed harmonics"
S.Voloshin, hep-ph/0406311

$$a^k a^m = \langle \sum_{ij} \sin(\varphi_i^k - \Psi_R)\ \sin(\varphi_j^m - \Psi_R) \rangle$$

Expect $\quad a^+ a^+ = a^- a^- > 0; \quad a^+ a^- < 0$

Strong CP violation: experimental studies

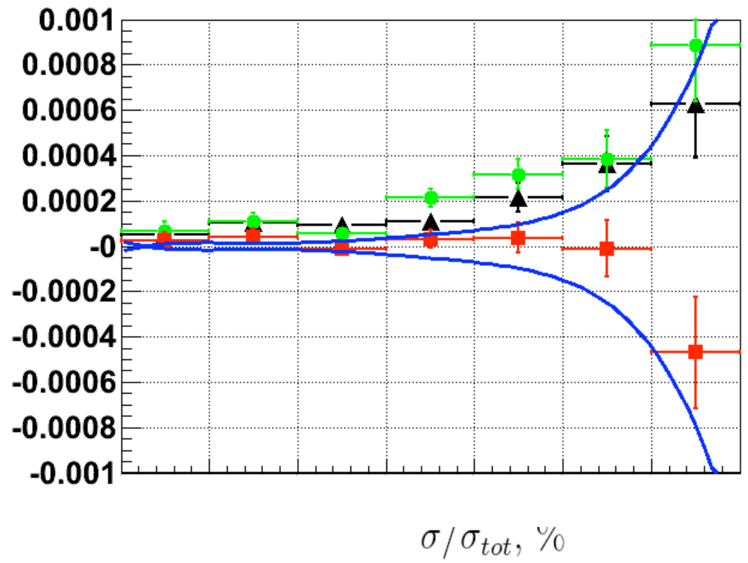
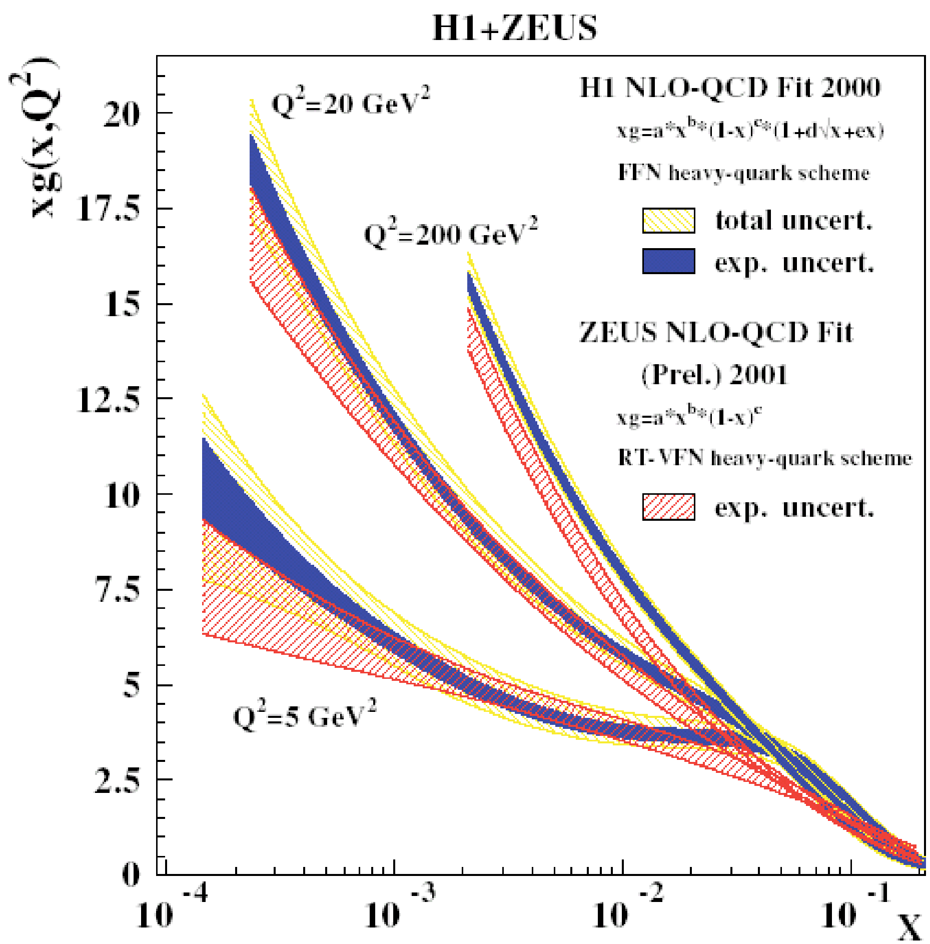


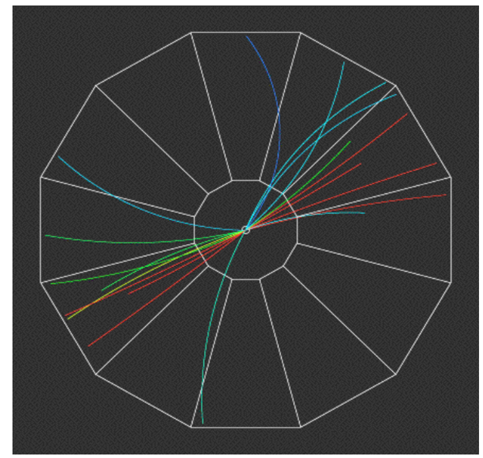
Figure 2: Charged particle asymmetry parameters as a a function of standard STAR centrality bins selected on the basis of charged particle multiplicity in $|\eta| < 0.5$ region. Points are STAR preliminary data for Au+Au at $\sqrt{s_{NN}} = 62$ GeV: circles are a_+^2, triangles are a_-^2 and squares are a_+a_-. Black lines are theoretical prediction [1] corresponding to the topological charge $|Q| = 1$.

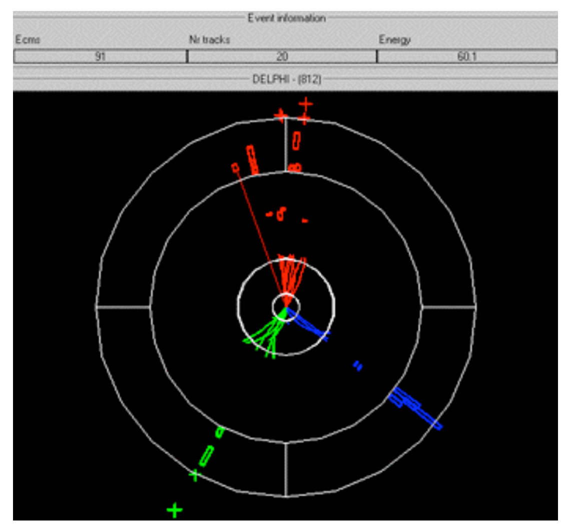
STAR Coll., nucl-ex/0510069; October 25, 2005

Need to analyze the systematics, improve statistics - vigorous ongoing work!

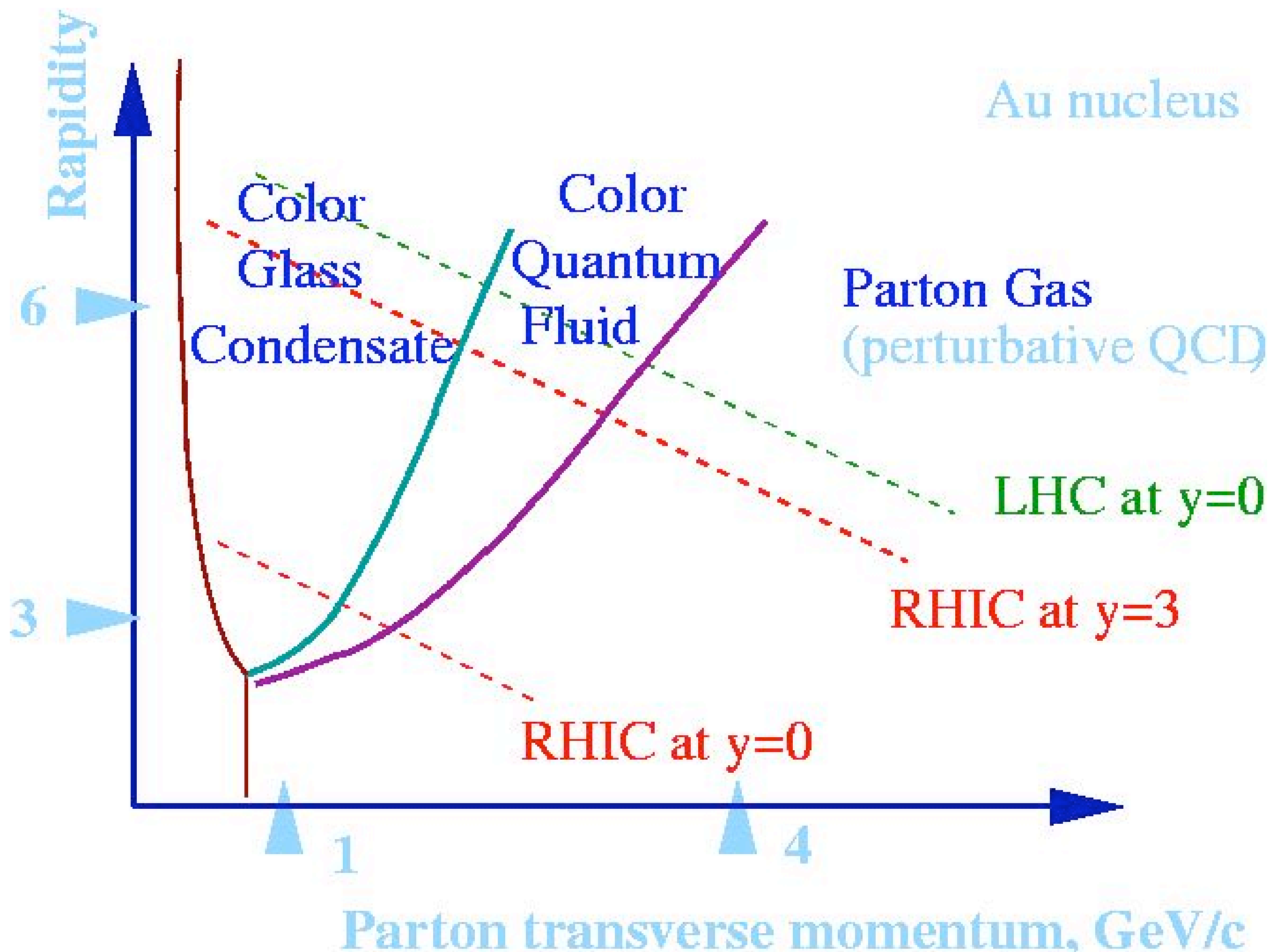
What are the wave functions of the proton and of the nucleus?





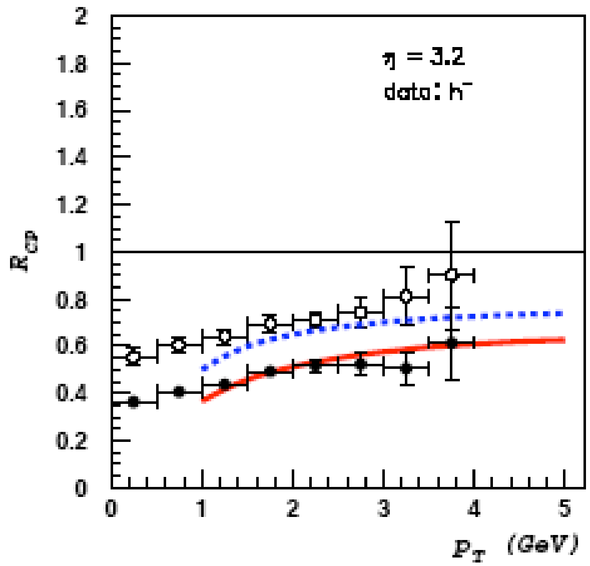


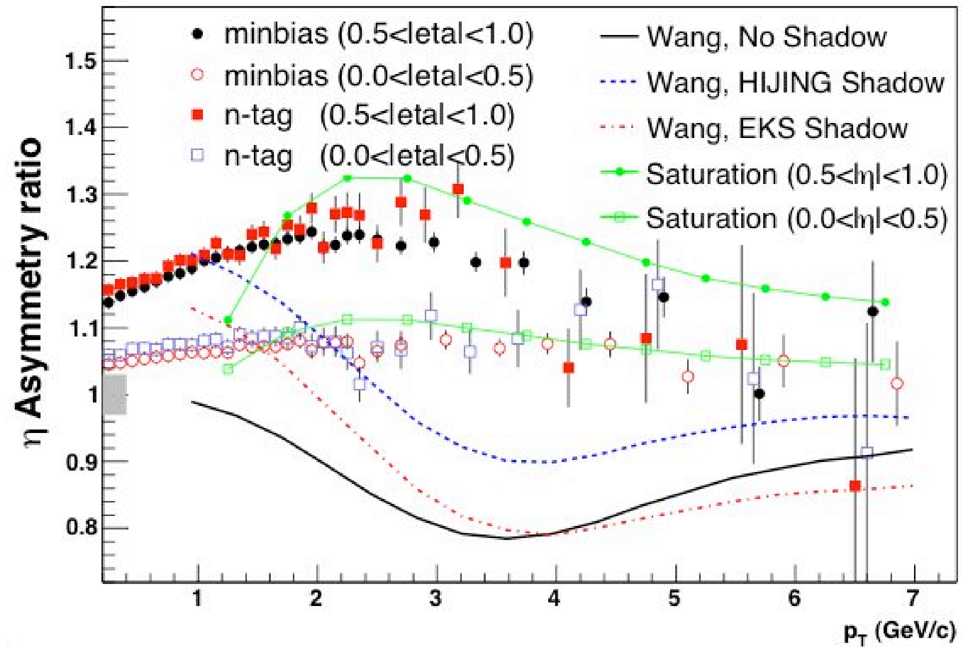
Phase diagram of high energy QCD



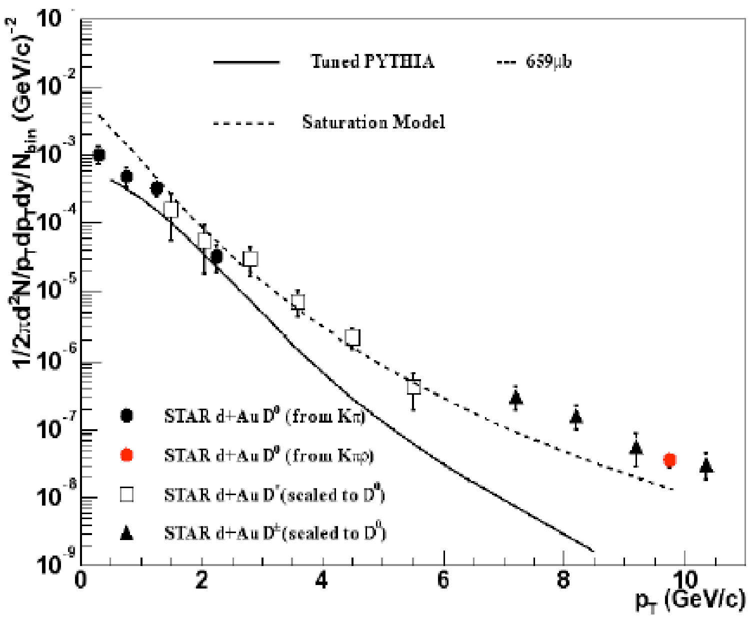
CGC confronts the data

hadrons





charm

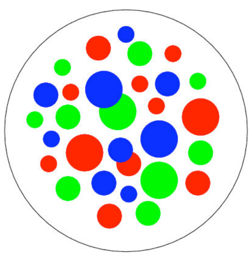


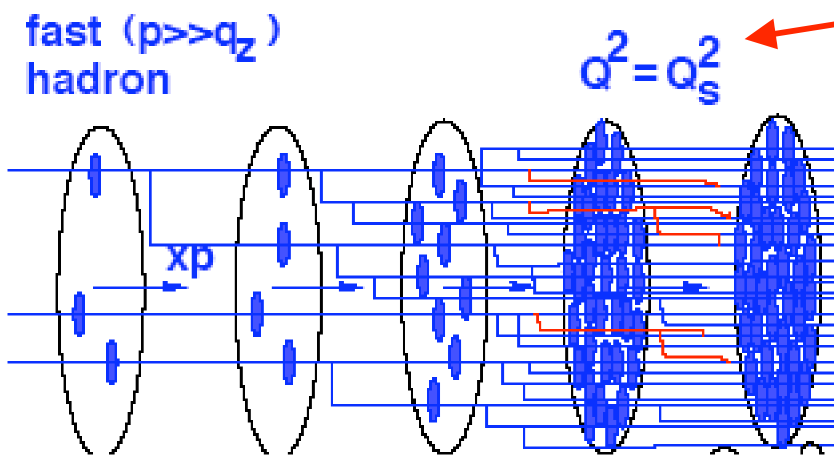
Building up strong color fields: small x (high energy) and large A (heavy nuclei)

Bjorken x : the fraction of hadron's momentum carried by a parton; high energies s open access to small $x = Q^2/s$

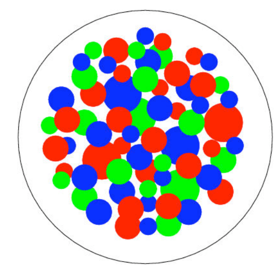
the boundary of non-linear regime: partons of size $1/Q > 1/Q_s$ overlap

Large x





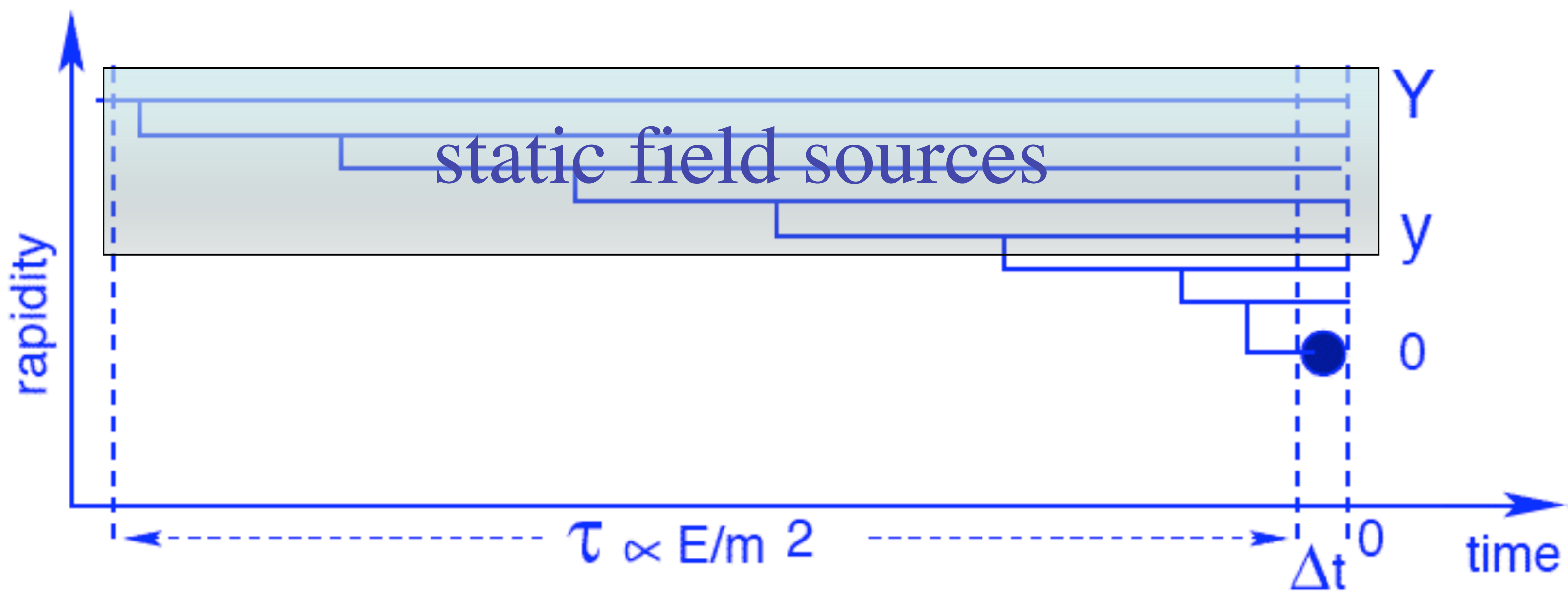
small x



Because the probability to emit an extra gluon is $\sim \alpha_s \ln(1/x) \sim 1$, the number of gluons at small x grows; the transverse area is limited

$\rightarrow$ transverse density becomes large

The origin of classical background field

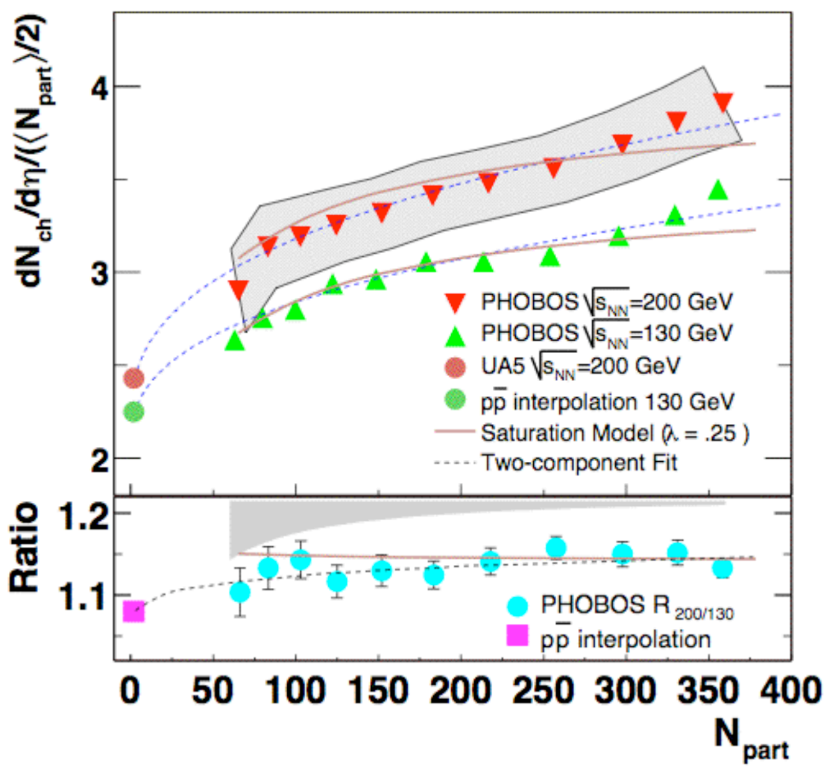


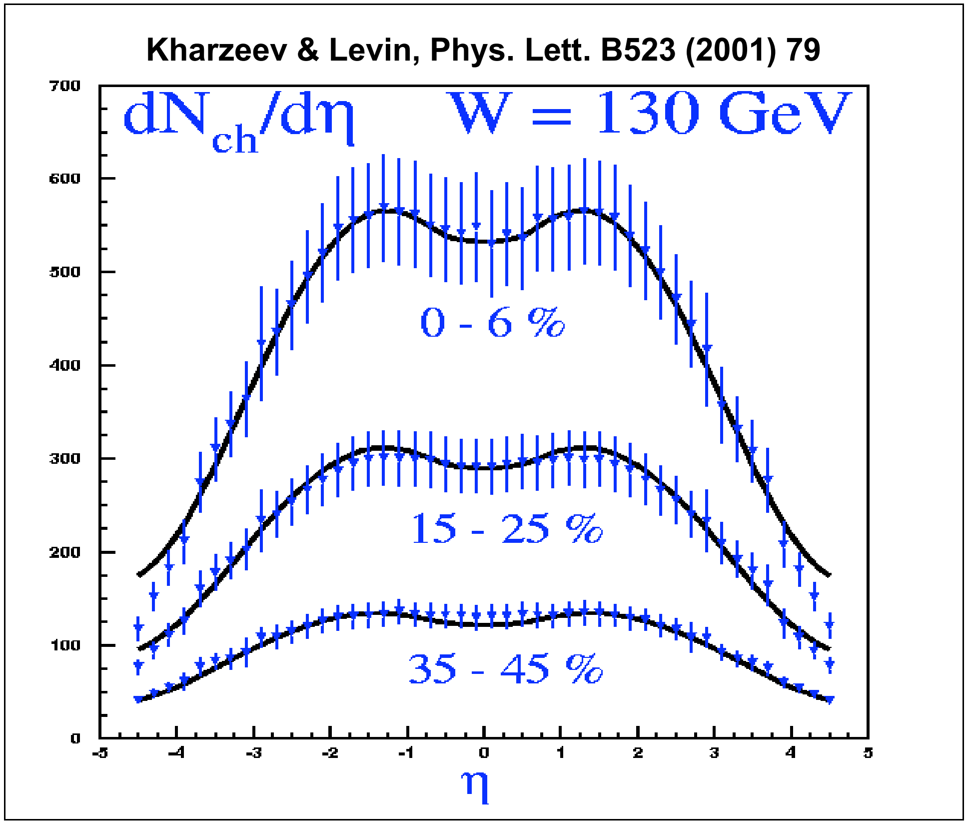
Gluons with large rapidity and large occupation number act as a background field for the production of slower gluons

"Color Glass Condensate"

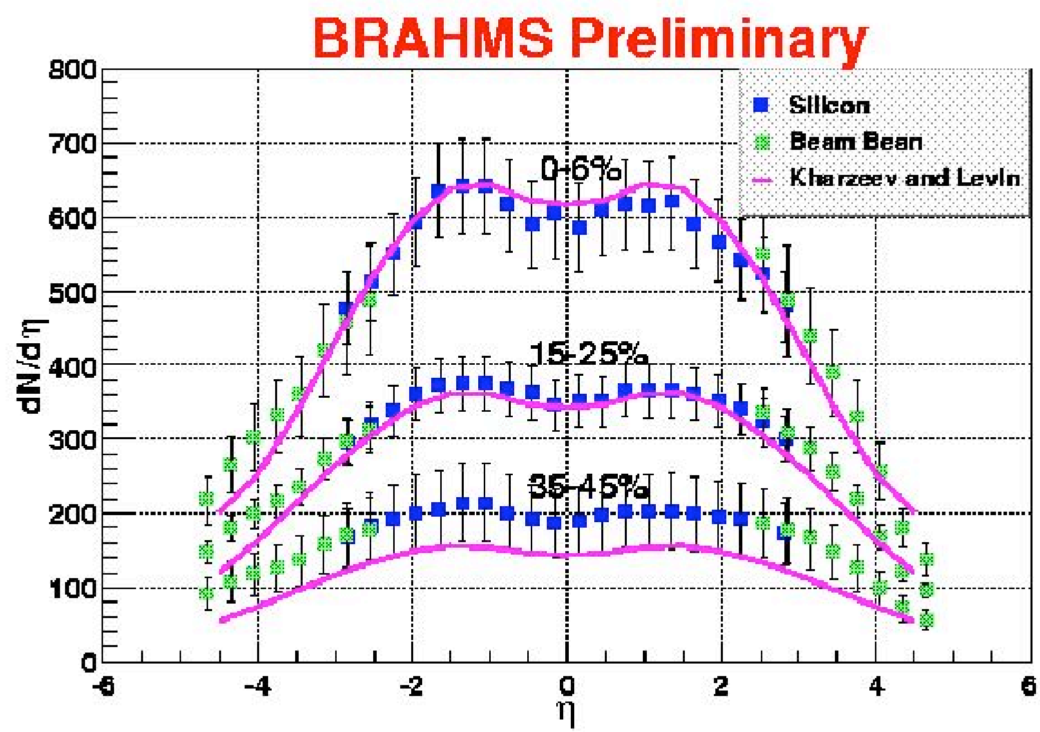
Classical QCD dynamics in action

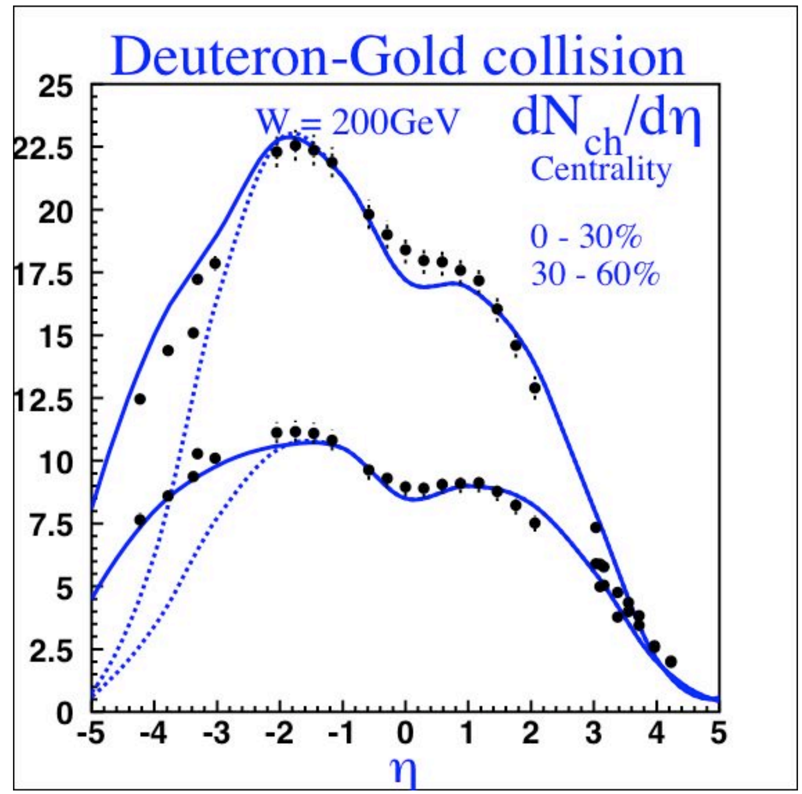
The data on hadron multiplicities in Au-Au and d-Au collisions support the quasi-classical picture





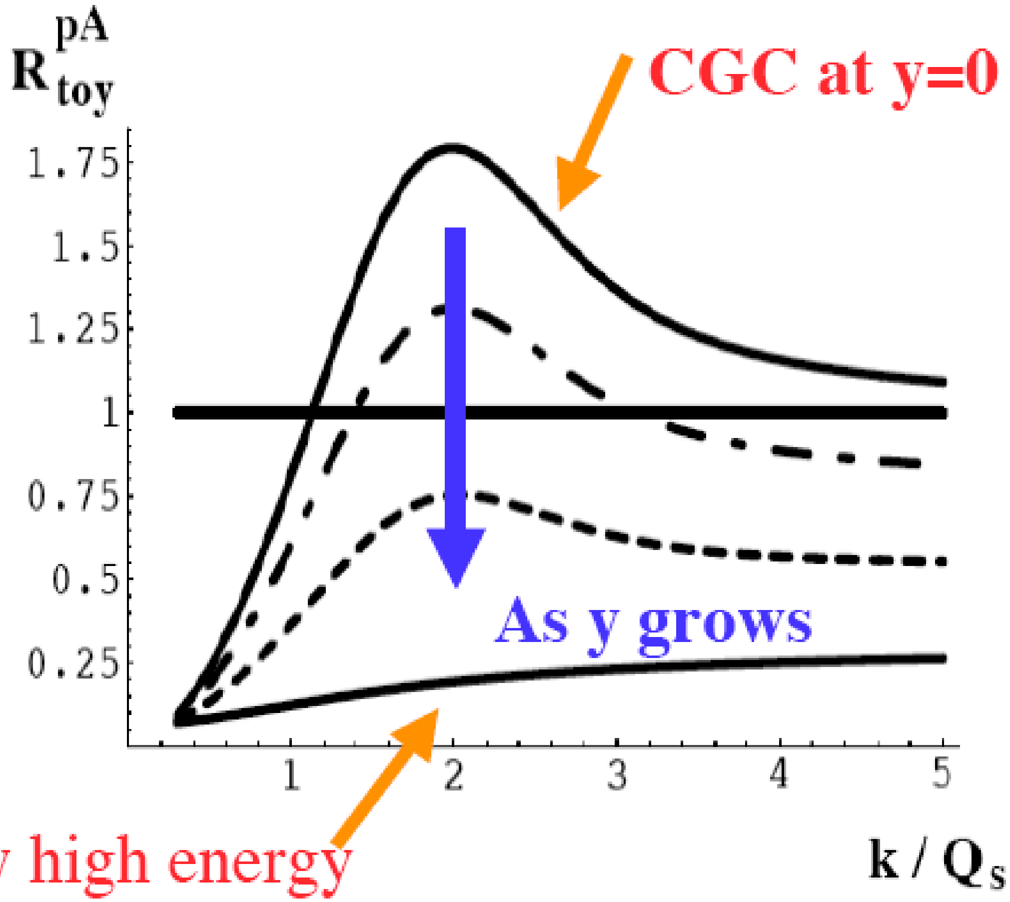
CGC and hadron multiplicities





Gluon multiplication in a limited (nuclear) environment

The ratio of pA and pp cross sections



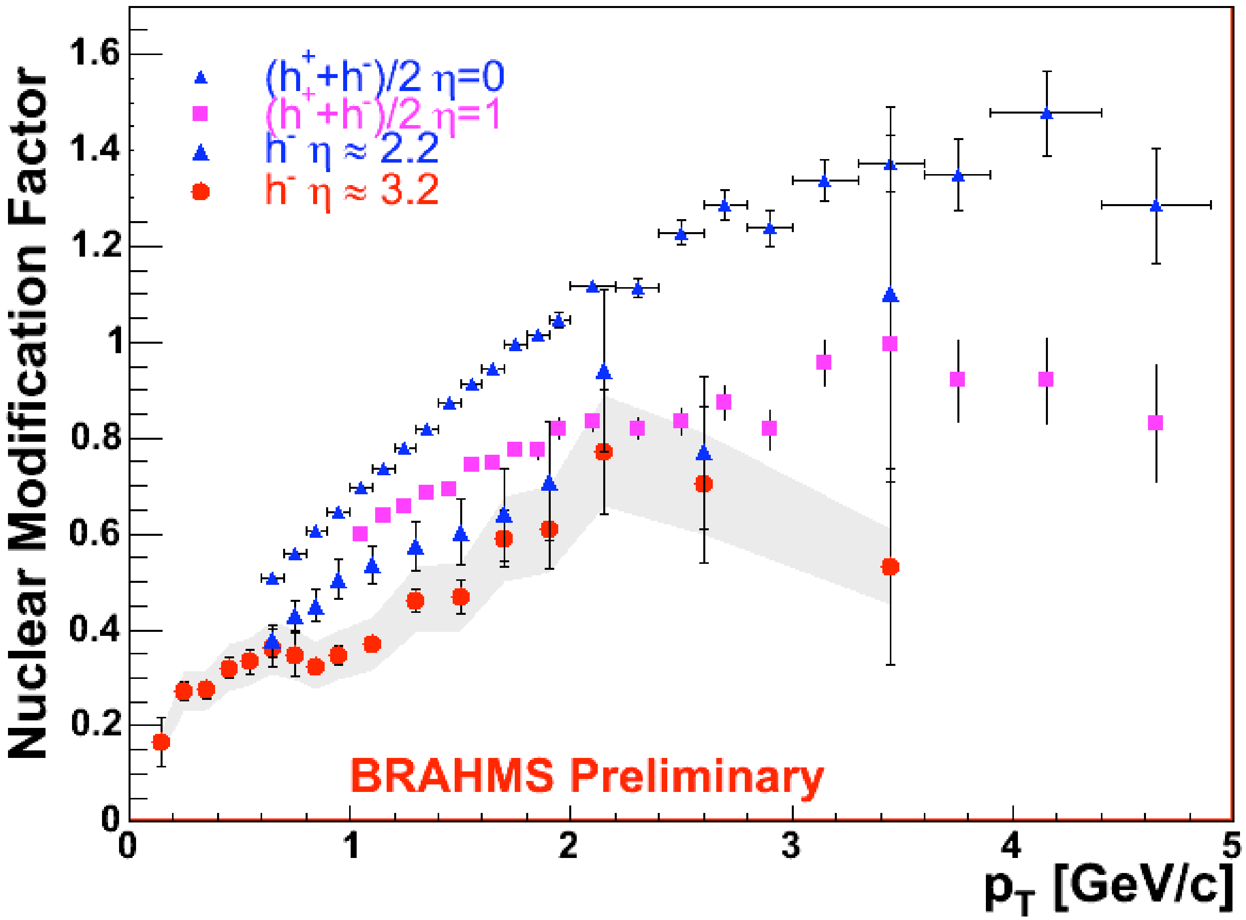
Very high energy

transverse momentum

DK, Levin, McLerran; Albacete,Armesto,Kovner, Wiedemann; DK,Kovchegov, Tuchin

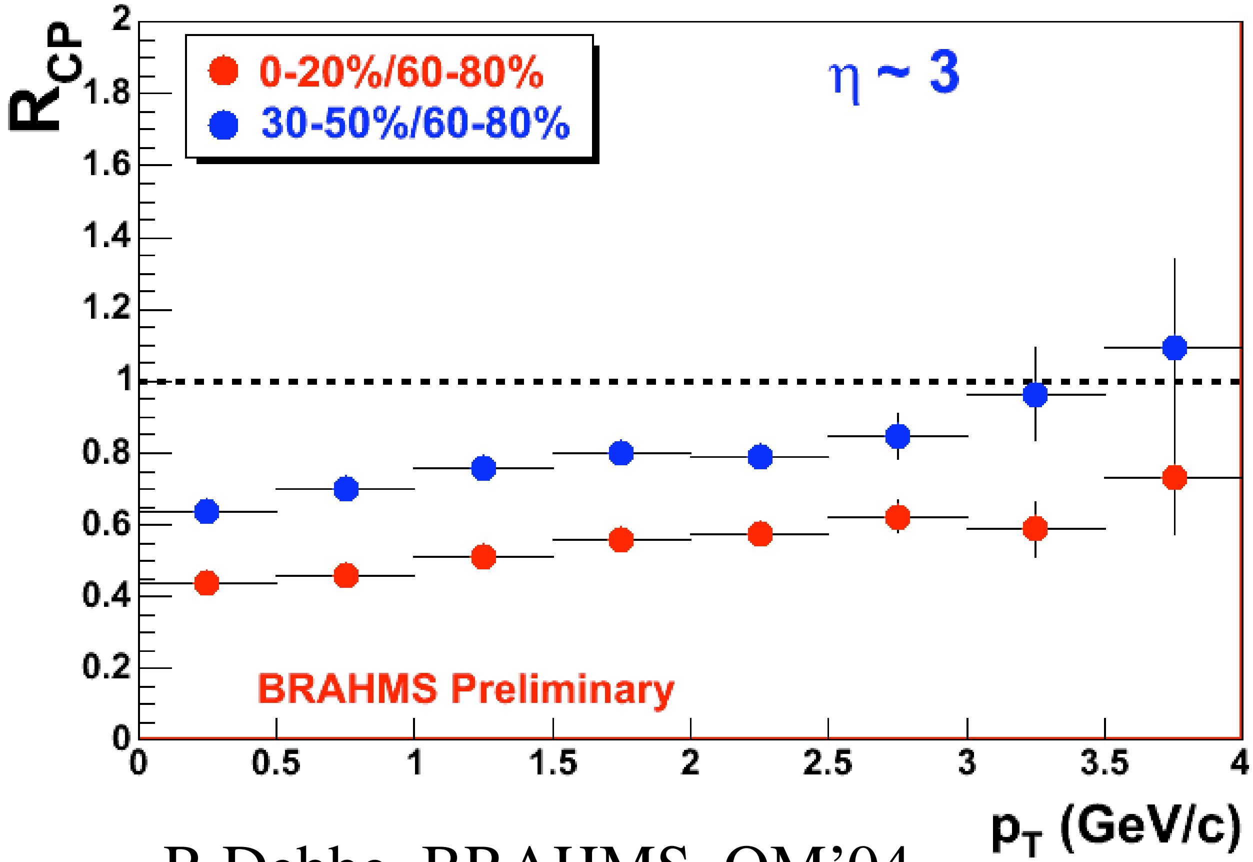
At large rapidity y (small angle) expect suppression of hard particles!

Nuclear Modification of Hard Parton Scattering

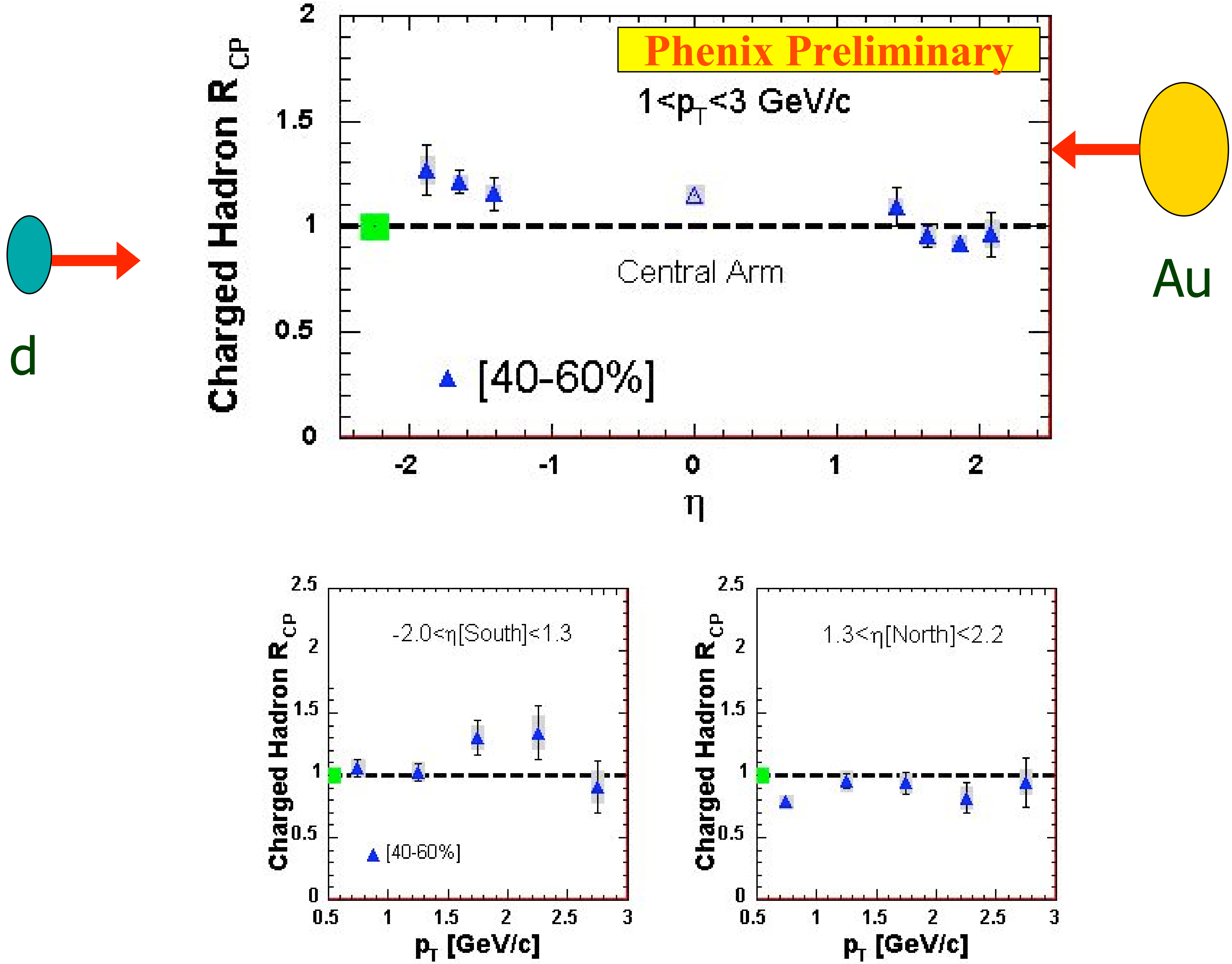


R.Debbe, BRAHMS, QM'04

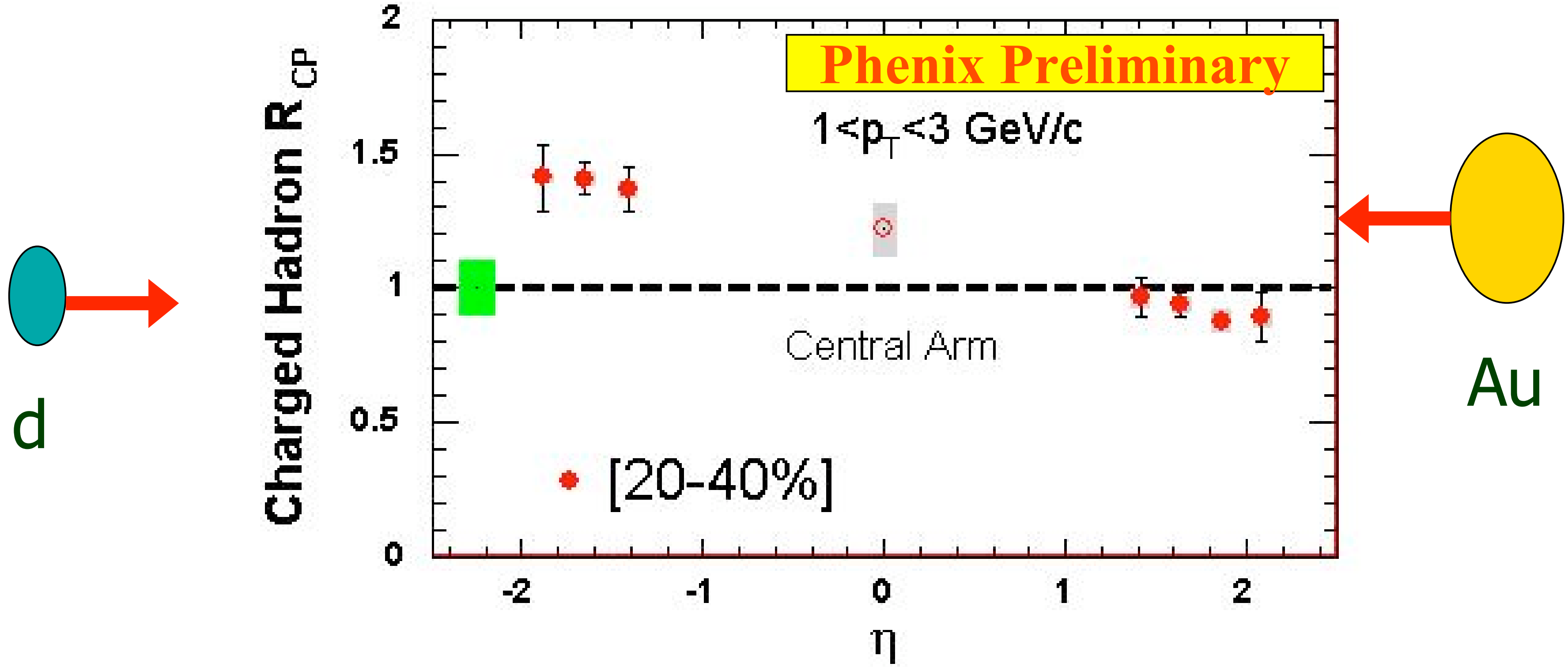
Centrality dependence

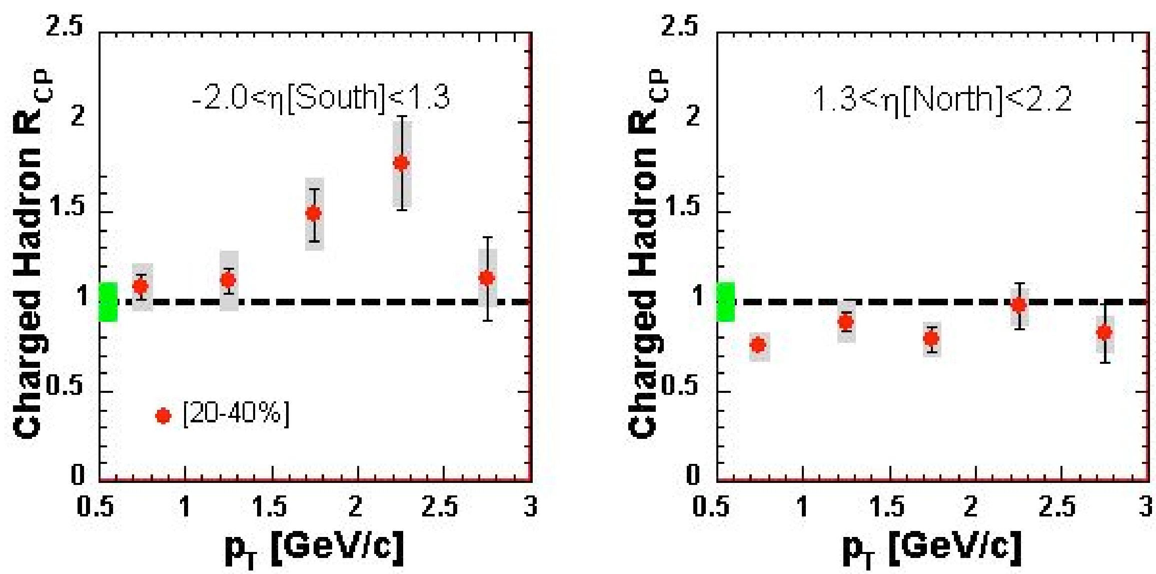


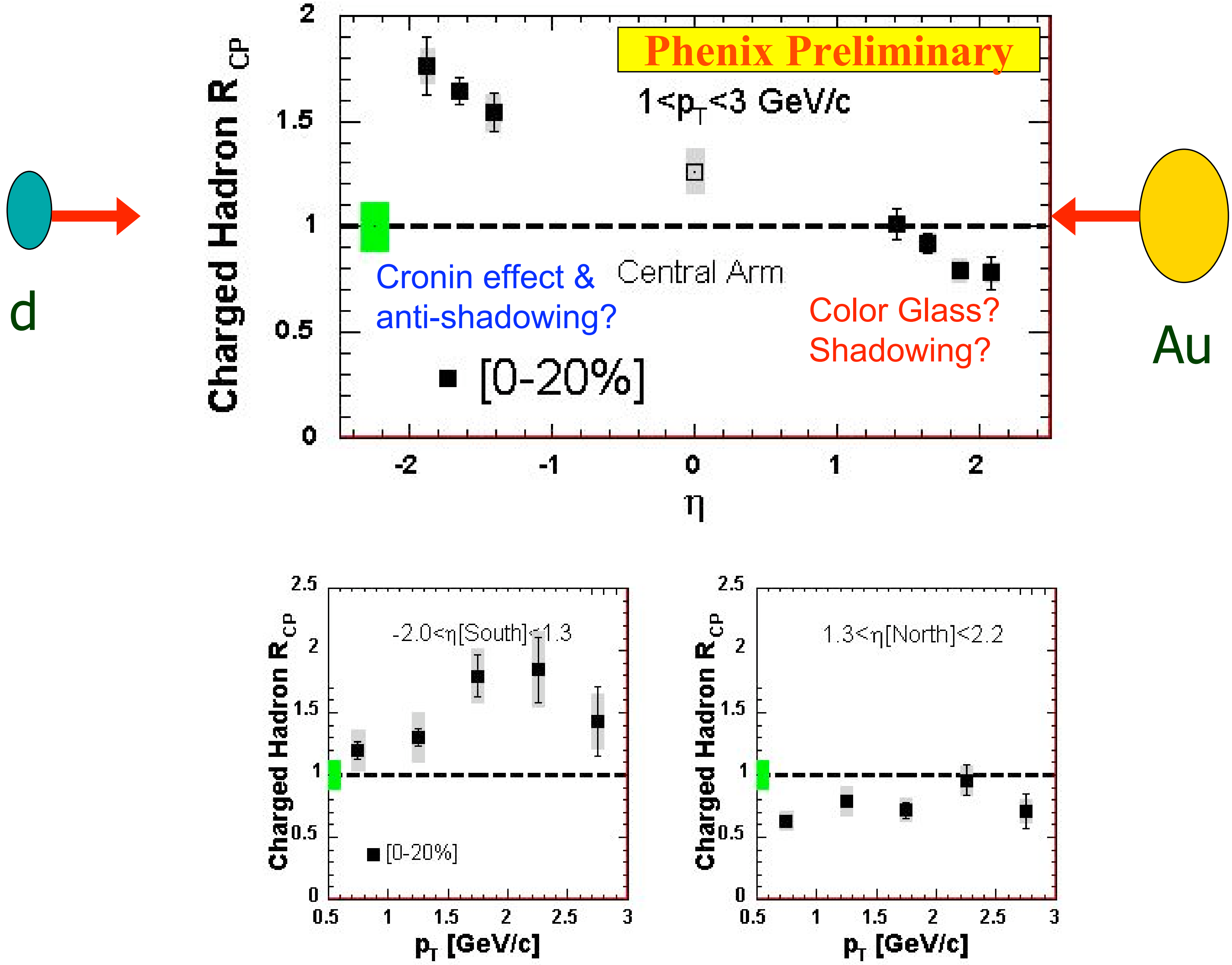
R.Debbe, BRAHMS, QM'04



Phenix Preliminary
1<p_T<3 GeV/c
Charged Hadron R_CP
Central Arm
[40-60%]
η
d
Au
-2.0<η[South]<1.3
1.3<η[North]<2.2
p_T [GeV/c]

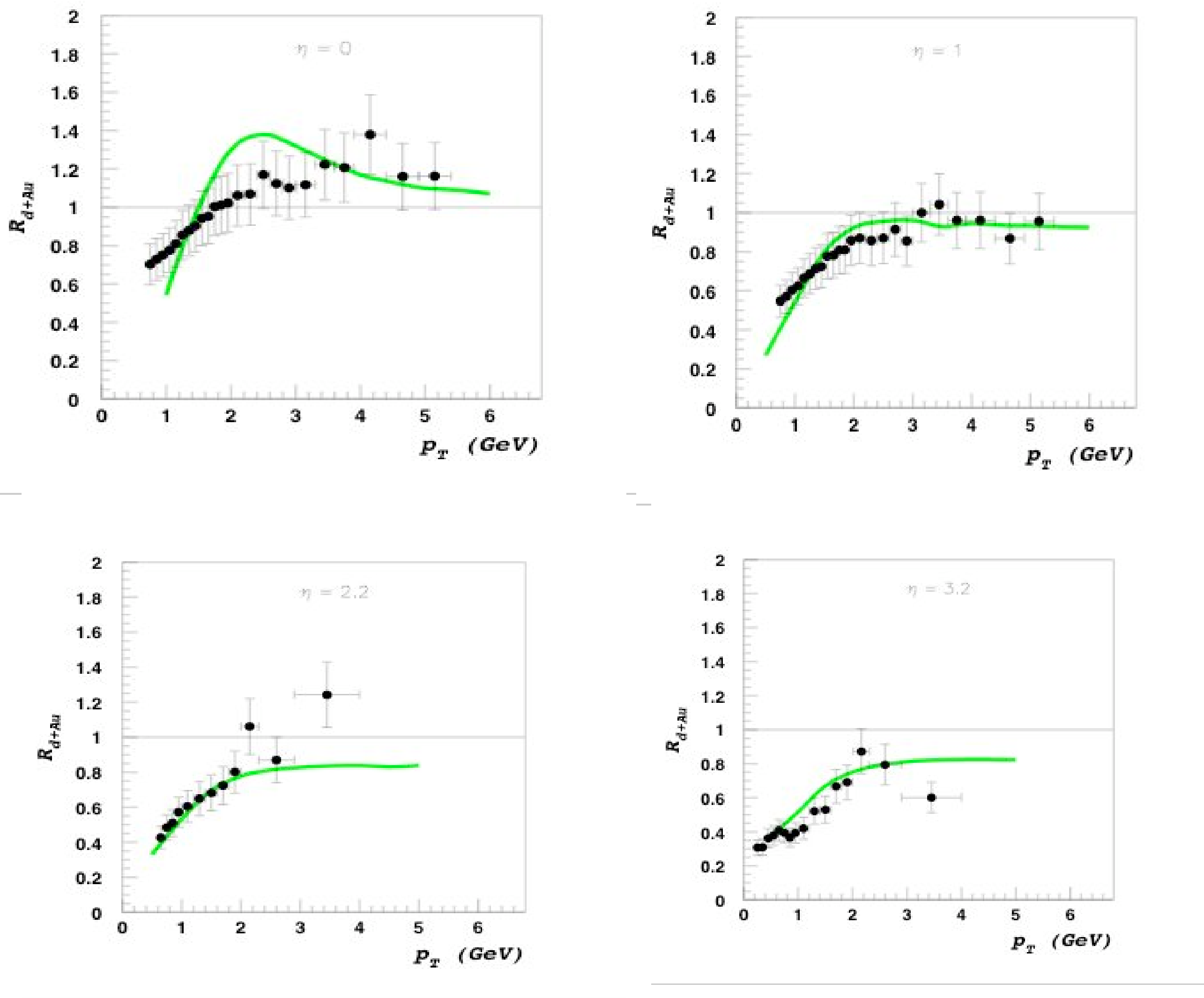

Phenix Preliminary
1<p_T<3 GeV/c
Charged Hadron R_CP
Central Arm
[20-40%]
η
d
Au
0
0.5
1
1.5
2
-2
-1
0
1
2


-2.0<η[South]<1.3
[20-40%]
Charged Hadron R_CP
p_T [GeV/c]
1.3<η[North]<2.2
Charged Hadron R_CP
p_T [GeV/c]
0
0.5
1
1.5
2
2.5
3



Phenix Preliminary
1<p_T<3 GeV/c
Charged Hadron R_CP
η
Cronin effect &
anti-shadowing?
Central Arm
Color Glass?
Shadowing?
[0-20%]
d
Au
-2.0<η[South]<1.3
1.3<η[North]<2.2
p_T [GeV/c]

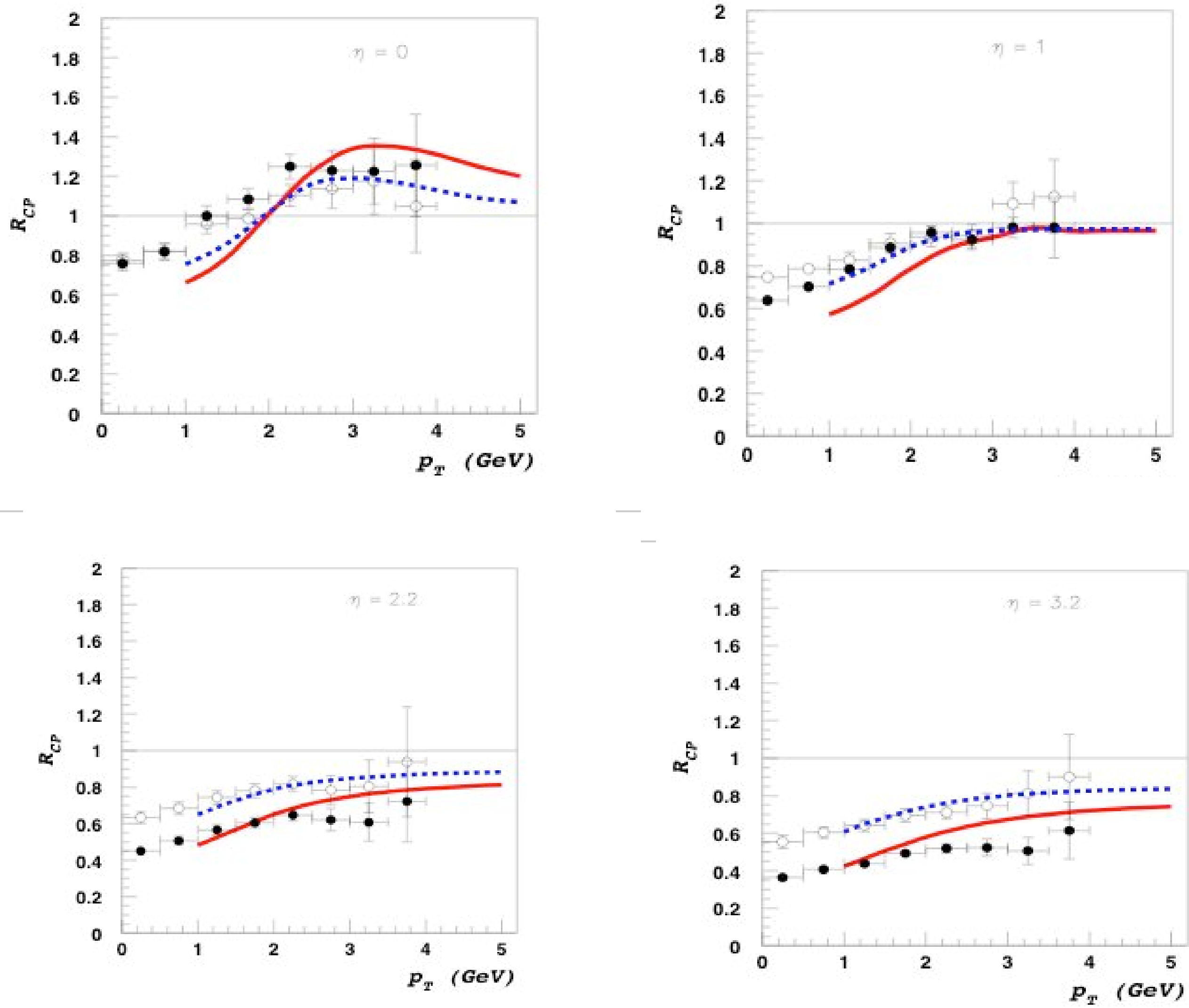
Color Glass Condensate: confronting the data



BRAHMS data,
η= 0, 1,
2.2, 3.2

DK, Yu. Kovchegov, K. Tuchin, hep-ph/0405045

Color Glass Condensate: confronting the data



BRAHMS data, R_{CP}
$\eta = 0, \quad 1, \quad 2.2, 3.2$

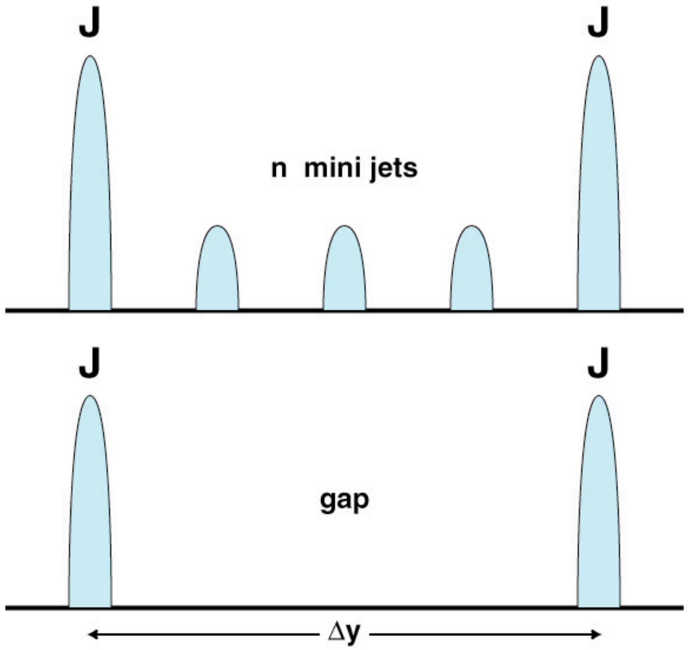
DK, Yu. Kovchegov, K. Tuchin, hep-ph/0405045

Are the effects observed at forward rapidity due to parton saturation in the CGC?

- Back-to-back correlations for jets separated by several units of rapidity are very sensitive to the evolution effects

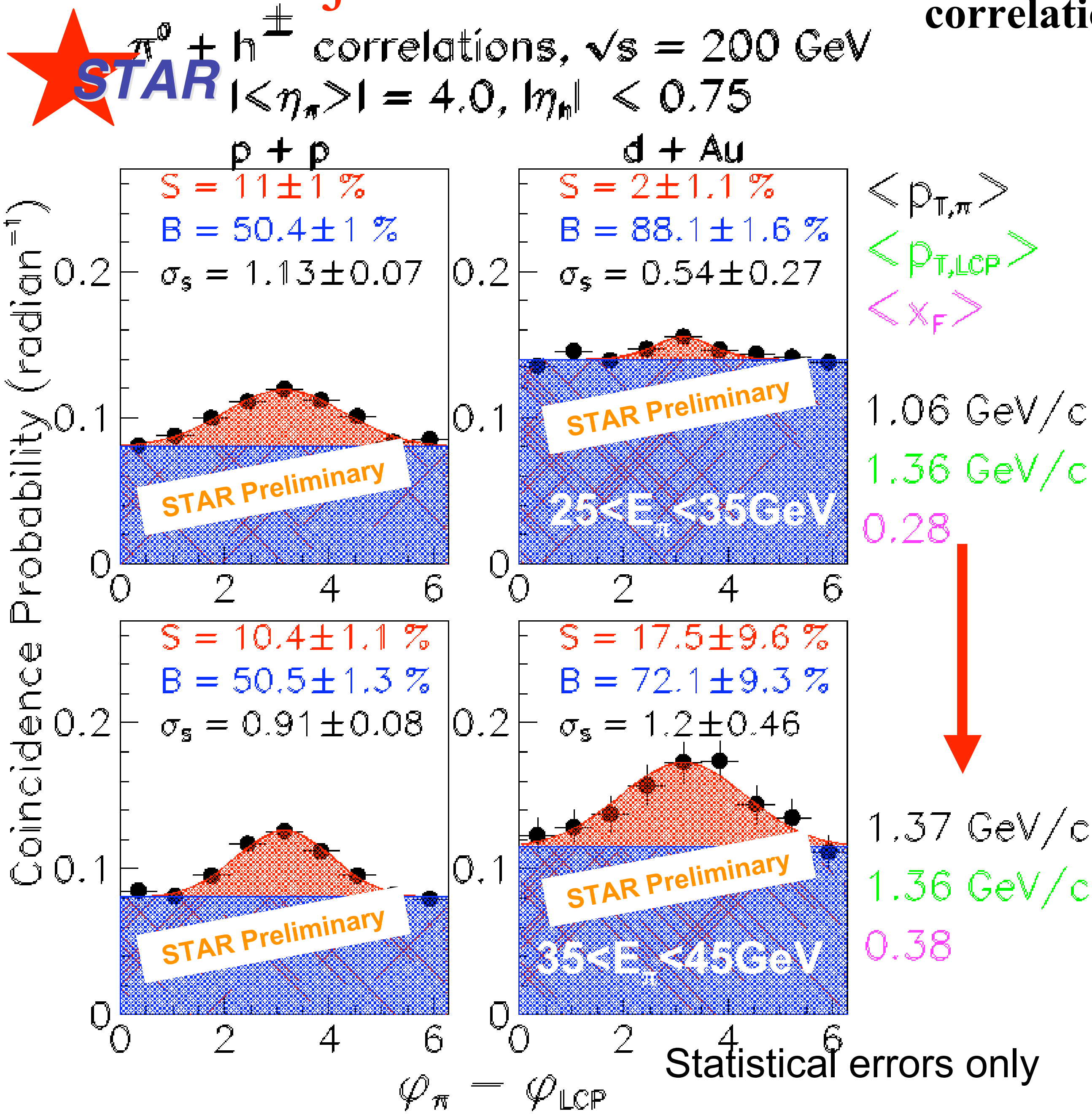
  ("Mueller-Navelet jets")

  and to the presence of CGC



Forward measurements at RHIC-II:
Do back-to-back correlations really disappear?

Monojets in dA are back

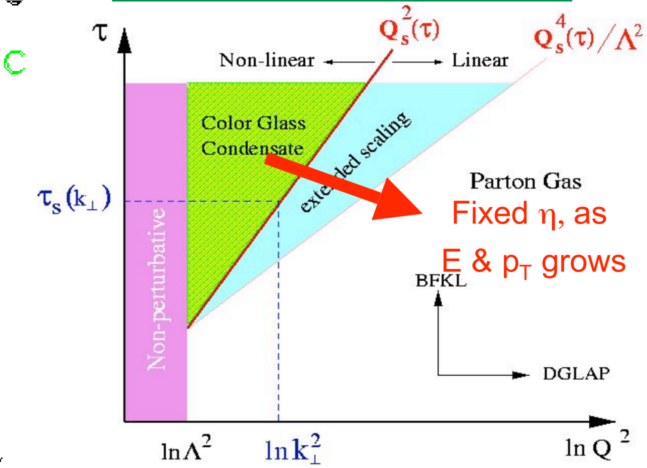


Large rapidity gap π^0+$h^\pm$ correlation data…

- **are suppressed in d+Au relative to p+p at small $\langle x_F \rangle$ and $\langle p_{T,\pi} \rangle$**

S_{pp}-S_{dAu}= (9.0 ± 1.5) %

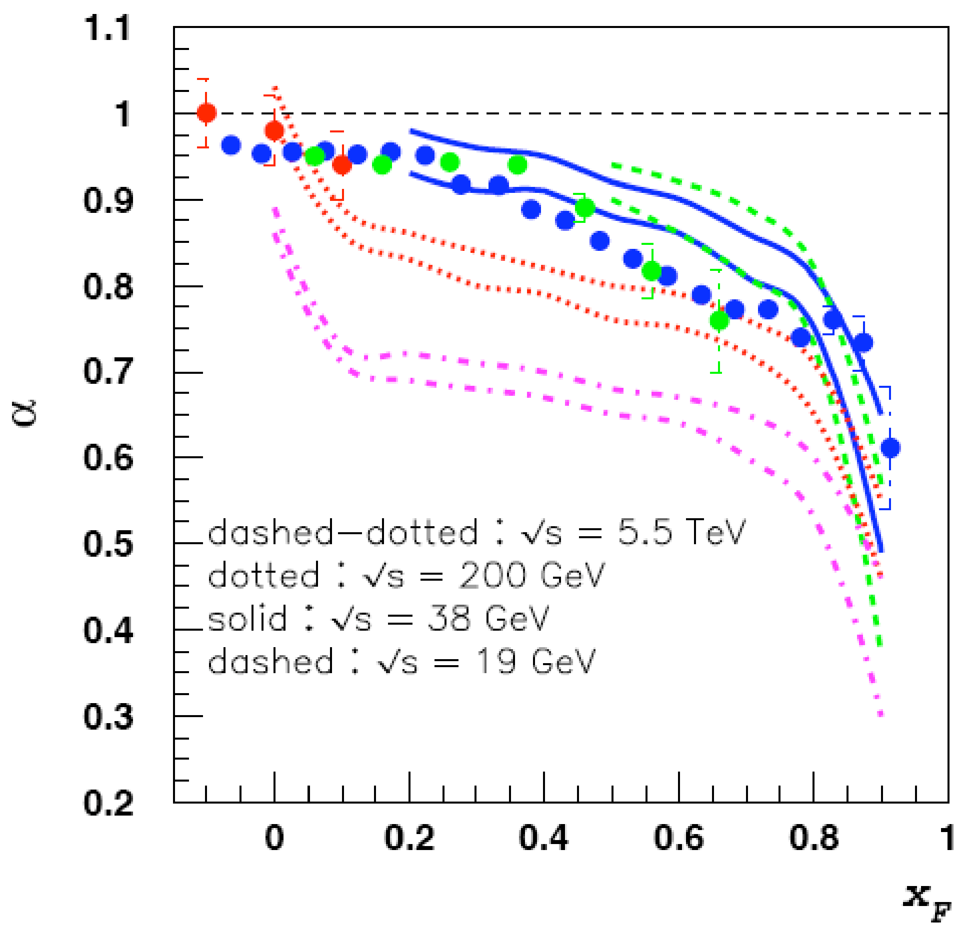
Consistent with CGC picture



- **are consistent in d+Au and p+p at larger $\langle x_F \rangle$ and $\langle p_{T,\pi} \rangle$**

as expected by HIJING

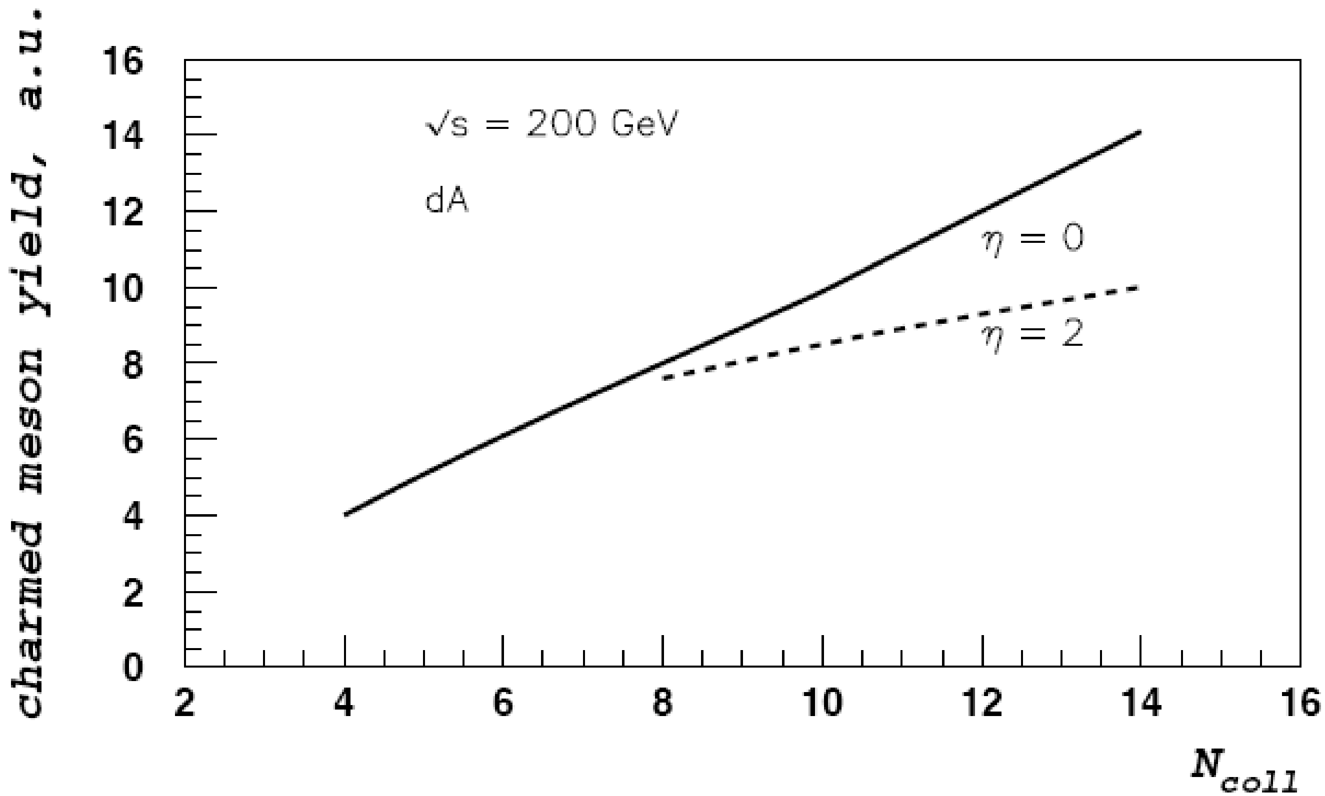
Are J/Ψ's suppressed at forward rapidity?



DK,K.Tuchin,
hep-ph/0510358

Are heavy quarks suppressed at forward rapidity?

DK,K.Tuchin, hep-ph/0310358



Summary

1. RHIC program aims at understanding the phase structure of QCD, the bulk non-equilibrium dynamics of gauge theories, and the structure of the nucleon and nuclei

2. A very significant experimental and theoretical progress has been made in the first five years of RHIC operation, and much more is expected